Knowledge Structures and Physics Teaching

by

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A thesis submitted in partial fulfilment of
the requirements for the degree of
Master of Science

Department of Physics
University of Canterbury
January, 1990

Acknowledgements

I am most grateful to Dr. Phil Butler, my supervisor, for his guidance and invaluable assistance throughout the year.

I would like to also thank:

The teachers and pupils of the high schools in Christchurch and Singapore, and the first year students, graduate students and lecturers of the physics department who kindly participated and helped in the data collection.

Staff of the physics department for their total support and assistance.

The executive council of the Rochester and Rutherford hall for their assistance in enabling my attendance at the ASPEN conference.

All others who in some way or other helped towards the production of this thesis.

Special thanks to Paul Russell, Psychology department, for his constant encouragement and kind assistance.

Contents

List of Tables

List of Figures

ABSTRACT

This thesis reports on my studies of the state of knowledge, conceptions and knowledge structures of students (aged 16-20) for geometrical optics, for mechanics and for physics as a whole. Several implications for teaching are deduced and recommendations are made to modify the knowledge structure of the students through conceptual frameworks, organisation of the content learnt, word associations and discussion of knowledge structures formed through free card sorting exercises.

It is found that due to content learning students have developed knowledge structures which are governed by a single surface feature or a group of related surface features. Students misinterpret physical situations and demonstrate misconceptions due to their lack of comprehension of the principles of physics. Those who have studied the subject matter in a series of gradations over 2 to 3 years have practically no wrongly construed conceptions in that area of study. I give examples to show that the level of misconceptions amongst the students reduces when they have related higher level knowledge. Alternative conceptual frameworks are proposed to influence the content oriented knowledge structure of the students.

The cognitive structures of novices (year 1 students) and experts (graduates students and university lecturers) have been studied and compared through 7 different free card sorting exercises. It is found that the cognitive structures of the subjects is a combination of mainstream physics labels, main categories, subcategories and physical constructs mentioned in the texts and used for teaching the subject. Some examples of the knowledge structures of the experts and the novices are given and a general cognitive structure encompassing the features portrayed in the individual knowledge structures of the subjects has been propounded.

Chapter 1

Introduction

Knowledge structure is the information processing term for organised networks of information stored in semantic memory (Champagne et al, 1981). Knowledge structure is required for retention of subject matter and for transfer of learning to different situations (Shavelson, 1974). Since the 1970's much research has been done to determine the conceptions and knowledge structure of students(see review article by Gilbert and Watts, 1983) and of the influence of students' past experience on the learning process. It has been shown that what teachers perceive to be taught is not what students learn (see review article by Driver and Erickson, 1983). These studies have also shown that the conceptions of students are not in line with the general theories of physics.

The studies in this thesis have concentrated on determining the conceptions and knowledge structure of students in physics. Geometrical optics and mechanics have been chosen because they feature as major components in high school science and in first year university physics courses in many countries. The studies show that students learn by content and develop structures characterised by surface features. Concept learning is proposed through the formulation of conceptual frameworks to modify the knowledge structures of students. The implications for teaching are discussed and alternative approaches are recommended to determine students conceptions prior to instruction and to modify these conceptions.

Questionnaires and interviews have been used to determine the knowledge base and knowledge sturctures of form 5 students (aged: 15yr.) to year 1 physics undergraduates (aged: 18-19yr.). Free card sorting exercises have been administered to determine the knowledge structures of novices (year 1 physics undergraduates) to experts (university lecturers teaching first year physics courses). The conceptions of students have been related to the knowledge base of the students and the knowledge required to comprehend and produce correct conceptions. The knowledge base and knowledge structures of students and lecturers have been used to propound a general knowledge structure for physics teaching and learning. For each of the studies the implications for teaching have been discussed and in some cases an alternative approach of conceptual learning is recommended.

The thesis is organised into five chapters and an appendix. Chapter 1 gives an overview of the studies performed in this thesis. Chapters 2 and 3 deal with the conceptions and state of knowledge of students in geometrical optics. Chapter 4 discusses the knowledge and conceptions of students in mechanics and shows that these are interrelated. In chapter 5 the knowledge structures of experts and novices are studied and compared. The appendix contains two papers that have been published and the instruments used in the studies. An overview by chapter is given in the ensuing paragraphs.

In chapter 2, the propagation and reflection of light are discussed to report on the conceptions and state of knowledge of students from form 5 to the first university year, to determine how students classify this knowledge, to propose an alternative mode of conceptually classifying the knowledge and to propose a plausible approach for teaching the concept of reflection. It is found that students classify using content and form classification groups using surface features. The approach in physics texts is critically reviewed and an alternative conceptual teaching method recommended. This chapter has been submitted for publication in the British journal *Physics Education.*

In chapter 3 the conceptions, state of knowledge and knowledge structure for refraction of form 5 students to first year undergraduates are discussed. Eight examples of the refraction of light are used to highlight the state of knowledge and conceptions of students. Through the answers of the students, their knowledge structure has been formulated. It is found that the teaching and learning of refraction is characterised by content learning. When confronted with a situation, students are generally able to answer only if it fits a content group within their knowledge structure. Each content group is governed by a single surface feature or a small group of related surface features. An alternative conceptual framework encompassing refraction is proposed for the teaching of refraction and to help in modifying the conceptions of students. This chapter has been submitted for publication to the European journal titled *International Journal of Science Education.*

Chapter 4 discusses the knowledge and conceptions of students aged 16 to 20 years for five different sections of mechanics namely linear motion, circular motion, curved motion, oscillatory motion, and connected particles and motion along inclined planes. Questionnaires were administered and interviews conducted to show that students misinterpret physical situations and demonstrate misconceptions due to their lack of prerequisite knowledge and their lack of comprehension of the principles of physics. We have shown that students who have studied the subject matter in a series of gradations over 2 to 3 years, have practically no wrongly construed conceptions in that area of study. Eight examples are discussed to show that the level of conception amongst students reduces with the increment in knowledge required to correctly perceive and interpret the situation. This chapter has been submitted to the official journal of the National Association for Research in Science Teaching (USA) titled *Journal of Research in Science Teaching.*

In chapter 5 the structure of novices (first year physics students) and experts (graduate students and lecturers) have been studied through an adaptation of free card sorting and word association methods used for studying cognitive structures. Each subject performed 7 different sets of card sorting exercises comprising 4 sets of word groups, 2 equation sets and a group on principles and laws of physics. A general cognitive structure encompassing the features portrayed in the individual knowledge structures of the subjects has been propounded. Similarities are drawn between the knowledge structure of the subjects and the structure of physics as presented in texts used in first year university courses. It is shown that the structure of the subjects is a combination of mainstream physics labels, main categories, subcategories, and physical constructs mentioned in the texts and used for teaching the subject. Word groups have been studied to determine associations between pairs of words and the classification of words applicable to more than one mainstream in physics. The structures propounded and common associations of words and equations are highlighted for usage in teaching lateral and longitudinal connections within the structure of the subject. This chapter has been submitted to the American journal *The Physics Teacher.*

Appendix A includes 2 further papers that have been published. The first titled *Geometrical Optics: Knowledge of students* discusses the state of knowledge and conceptions of students for the propagation of light, reflection and refraction. The implications for teaching and learning are discussed through recommendations for making the syllabus progressive over the school years of the learner and the teaching less content oriented and more conceptual. This paper was presented at the Asian Physics Education Network conference/workshop held in Melbourne from 23 - 27 September 1989.

The second paper titled *The Science Roadshow 1988: The Effects of pupils* was published in the *The NZ Science Teacher* studies the effect on students of hands on experience in promoting science. The students were provided with a variety of exhibits which cater to the interests of most students. Pre and post questionnaires were administered to determine the change in attitudes and interest in science. The implications of the roadshow as an alternative means of teaching are discussed.

Chapter 2

Reflection of Light: Conceptions, Structure and Approach

2.1 Introduction

In the past two decades, there have been many studies of the conceptions and influence of students' past experiences on the learning process. Much of the research has concentrated in elementary Mechanics and Electricity and it has been shown that what teachers perceive to be taught is not what students learn (see the review articles: Driver and Erickson, 1983; Gilbert and Watts, 1983). Less research has been done in Optics. Optics involves more abstract observations, whereby the result observed is not physically connected to the causal effect. Students conceptions and their state of knowledge have been measured by Guesne (1981) and Jung (1981) for reflection off a plane mirror; Stead and Osborne (1981) for propagation of light; and McDermott (1987) for images formed by convex lens. These studies have found that students hold certain conceptions that are not in line with the standard theories of light and reflection.

Light has been chosen in this study because it is widely taught in high schools and in first year university courses in many countries. Furthermore, the concepts that confront students in light are few and may be broadly categorised as propagation, reflection and refraction. Students know that objects cannot be seen without the presence of light but not much thought seems to be given to the processes which make this possible. Students go through four to six years of optics learning in secondary schools but the conceptual framework of the typical first year physics undergraduate lacks understanding (Singh and Butler, 1989a). In this paper propagation and reflection of light are discussed to: report on the conceptions and state of knowledge of students from form five to the first university year; determine how students classify this knowledge; and propose a plausible approach for teaching the concept of reflection.

Questionnaire	Questionnaire Description	No. of Questions	Content
Terms	Terms in Light	7	Terms used in reflection of light
Equations	Equations used in Reflection	6	Symbols of three equations had to be explained and their conditions of applicability stated.
General	General notions on light	7	Propagation of light and its effects.
Plane Reflection	Reflection in plane surfaces	5	Ray tracing and image determination.
Curved Reflection	Reflection in curved mirrors	9	Ray tracing and image determination in convex and concave surfaces.

Table 2.1: Questionnaire Description.

Group	Description	Age	No. of students
Form 5	Form 5 students from two schools in New Zealand	15 yr	31
Form 6	Form 6 students from two schools in New Zealand	16 yr	32
Form 7	Form 7 students from two schools in New Zealand	17 yr	36
S'pore	Pre-university 1 students from two schools in Singapore	16yr	29
NZ	First year New Zealand undergraduates reading physics	18yr	8
Foreign	First year foreign undergraduates reading physics in New Zealand	18yr	5

Table 2.2: Student groups who participated in the study.

2.2 Methodology

Five sets of questionnaires (see table 2.1), were administered to six different groups of students (see table 2.2) over a period of five weeks, prior to the optics teaching for that year. Each questionnaire consisted of short structured questions. Although no time constraint was applied in administering the questionnaires, none of the students took more than an hour to complete each. Students were interviewed wherever clear and direct inferences could not be made from their answers. The questions were made short and simple. Diagrams were provided in many instances to provide clarity.

The different questionnaires were uniformly distributed within each group for the form 5, form 6, form 7 and S'pore student groups. Each student in the NZ and Foreign student groups answered all the questionnaires. Students chosen were from schools that had geometrical optics as part of their school syllabus (New Zealand Department of Education, 1978). All the undergraduates participating had studied geometrical and wave optics in senior high school. The scoring for the questionnaires was performed as follows: 2 for a correct answer; 1 if a semblance of knowing the answer was portrayed; and 0 if the answer was totally wrong.

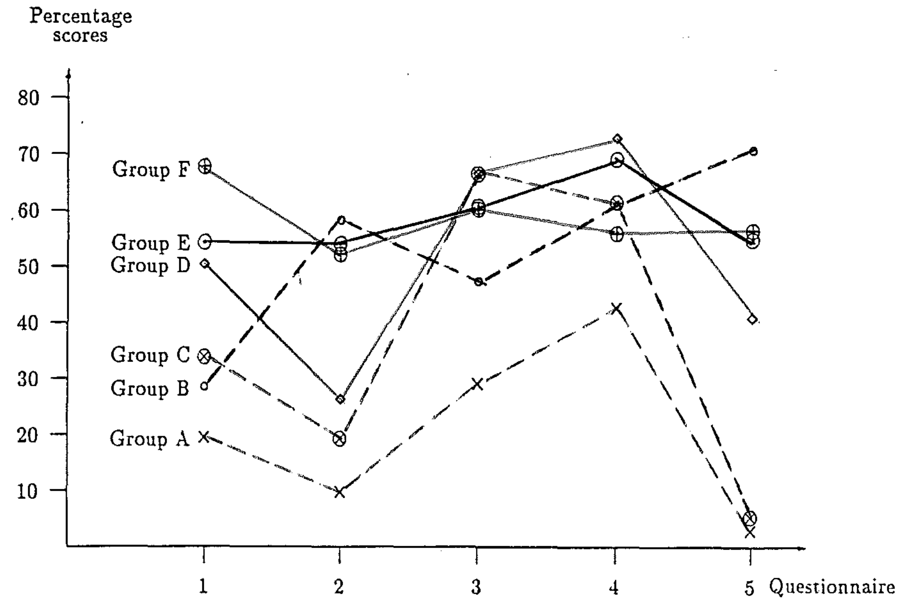

Figure 2.1: Mean percentage score for each group by questionnaire.

2.3 Research Findings

The fifth form students scored the lowest in every questionnaire (see figure 2.1). Although they had studied geometrical optics over four years their conception and understanding of the topic was low. This is an area of concern as basics are not being learnt in the earlier stages. The S'pore and Foreign students groups scored lowly in the equations questionnaire. Out of the three equations given, two were not covered in the syllabi in their countries. The pre-university students in Singapore had very low scores in the curved surfaces questionnaire as well. This is not taught in the schools there (Ministry of Education, Singapore, 1989). Students scored lowly wherever the application of principles to non-standardized situations was required. They performed well in standard type questions used as examples in the classroom and in textbooks. First year physics undergraduates did not perform significantly better than any of the other groups, excepting the form 5 students group.

2.3.1 Terms in Light

In this questionnaire, students were asked to *explain in detail* their understanding of terms they have encountered in their study of the reflection of light. However, only the physical features were used to describe convex and concave mirrors rather than using the properties of the mirrors or the nature of the images formed by the mirrors. In drawing the images formed by spherical mirrors (concave and convex), many drew the image correctly for an object at a distance greater than the focal length of the mirror. They seemed at a loss, when the object was placed at a distance equal to or less than the focal length of the mirror. Although the same procedure was needed, they could not apply it. In their explanations to some answers, students used the

GROUP	Form 5	Form 6	Form 7	S'pore	NZ	Foreign
Meaning of symbols	60.0	100	92.7	100	100	91.7
Conditions of applicability	0.0	62.5	71.4	16.7	43.8	33.3

Table 2.3: Group mean percentage scores for the law of reflection.

terms focal point, focus and focal length but could not explain the term principal focus. Of 33 students 14 knew the meaning of the term principal focus while only 5 realised that it was applicable to both mirrors and lenses. Some mentioned that it was a point to which rays parallel to the principal axis would converge or from which they would diverge. Only two mentioned its relationship to the centre of curvature.

Many were able to state the law of reflection as *the angle of incidence equals the angle of reflection* but were unaware of the condition that the incident ray, the reflected ray, and the normal at the point of incidence must lie in the same plane. Some specifically mentioned that the laws held only for mirrors as opposed to any smooth surface. Very few were able to generalise and apply the law to a non-plane, smooth surface.

2.3.2 Equations

Students were asked to state the meaning of the symbols used in three equations. Ninety percent of the students recognised the equation $\angle i = \angle r$ but could not state the conditions for its applicability. Table 2.3 shows the vast drop in scores when students were asked to state the conditions of applicability. They learn by content and symbolization, and lack the ancillary knowledge that goes with each equation.

2.3.3 General Notions on Light

Most students loosely knew the answer to the question *What is light?* When asked to be specific, apart from stating *it is a form of energy,* students had difficulty in elaborating further. The closest they came to describing light was *it is electromagnetic radiation and is in particle or wave form.*

The idea that light travels in straight lines and an obstruction in its path causes a shadow was well known but only 24% were able to relate it to the processes of reflection and absorption. Seven out of the 14 undergraduates used dark and bright bands due to interference and diffraction to account for shadow formation.

The answers to the question *How are we able to see objects that do not emit their own light?* may be categorised as follows: light incident on the objects is partially absorbed and the rest is reflected; light incident on the objects is reflected; and light is absorbed and re-emitted by the objects. Note that the third statement is wrong but can be traced to some elementary texts used in school science e.g. Bowden, Stonehouse and Vincent, 1972.

Studies involving mechanics, (McCloskey *et al* 1980; Gilbert *et al* 1982; Clement 1982 and McCloskey 1983) have shown that students have difficulty ignoring external

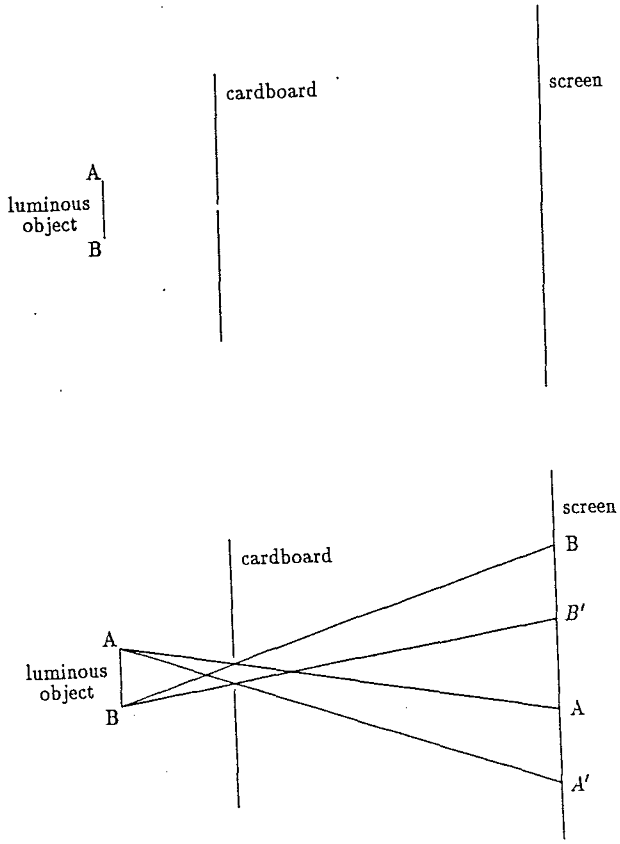

Figure 2.2: (a) Diagram of pinhole set-up (b) Overlap of images due to a larger pinhole.

effects in explaining ideal motion. In reflection the reverse seems to be true. Even in the case of diffuse reflection, the rules of regular reflection were often assumed. Regular reflection is ingrained in the minds of the students. The role of diffuse reflection for the observance of objects is totally neglected. They did not realise that reflection occurred in different directions due to the roughness of the surface. Most books just make a passing mention of diffuse reflection in the introductory stage, after which it is totally ignored. Students could not state the conditions under which these two types of reflection takes place. Seventy two percent used a plane mirror to explain the two terms stating that in regular reflection no absorption took place while in diffuse reflection part of the incident light was absorbed and hence only partially reflected.

Forty four percent of the students did not know all the conditions affecting the size of the image formed for the pinhole set-up of figure 2.2a. Except for the form 5 students, most knew how to use ray drawing to determine the image position and size. Sixty four percent knew that a larger pinhole would blurr the image or in their words make it *fuzzier*, but only a handful were able to elaborate further by using a ray diagram. (see figure 2.2b)

Students were asked to compare the brightness of the image formed in the set-up of figure 2.2a, to that of the images formed for a similar set-up using two pinholes.

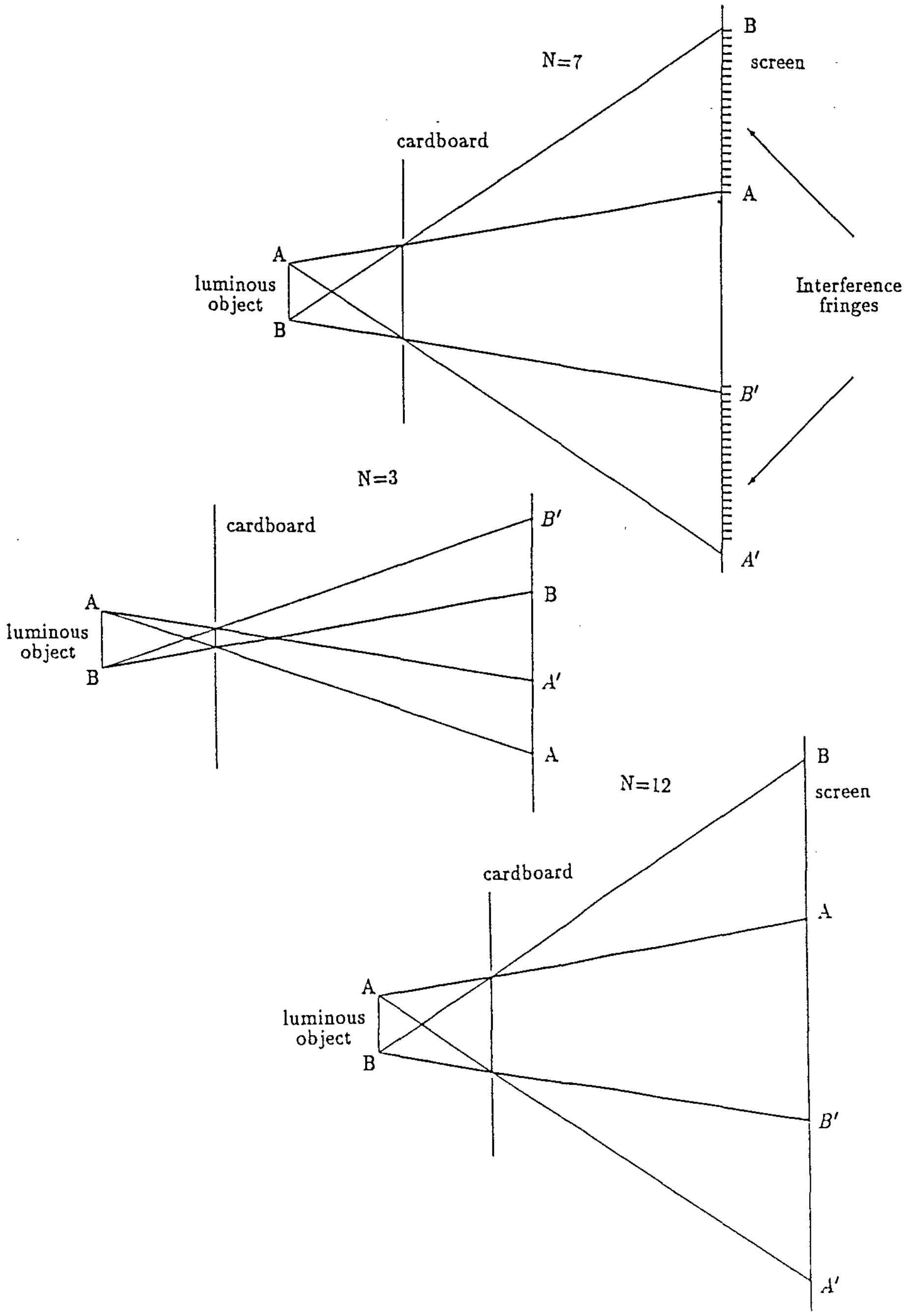

Figure 2.3: Images drawn for two pinholes ($N_{Total} = 35$).

GROUP	Form 5	Form 6	Form 7	S'pore	NZ	Foreign
Reflection off a single plane surface	92.9	80.0	88.9	83.3	100	100
Reflection off two plane surfaces	35.7	66.7	66.7	75.2	75.0	50.0
Reflection off a single curved surface	9.5	38.9	25.9	53.0	33.3	46.7
Image determination in a single plane mirror	0.0	50.0	55.5	58.3	12.5	60.0
Image determination in a single curved mirror	0.0	88.0	63.3	2.8	50.0	38.3

Table 2.4: Group mean percentage scores for the various reflection tasks.

None used the inverse square law governing intensity. Seventy six percent concluded that the brightness would be lesser for two pinholes, hinting that the energy split between the two pinholes. Those who took the pinholes close enough to obtain overlapping images stated: the brightness in the overlapping region would be double while that in the other region would be equal; or the brightness in the overlapping region would be equal while that in the other region would be half.

Those who drew the images distinctly separated stated that the brightness would be halved. Some senior students drew interference patterns but could not provide the reasoning for doing so apart from *there are two openings close together.* (see figure 2.3)

2.3.4 Reflection

Students were asked to: complete the path of a ray incident on different reflecting surfaces; and use ray drawings to determine the position of an image formed for reflection in different surfaces.

For most students *reflection* is considered synonymous to *plane mirrors.* The scores in table 2.4 show that students had little difficulty in drawing the path of the reflected ray for a smooth, plane surface. The scores markedly reduced when two reflecting plane surfaces were encountered. For the case of a smooth curved surface, the scores were even lower. Students were unable to apply the same principle and procedures to determine the image position for different situations. Figure 2.4 shows the path of the rays drawn by students, upon reflection off a smooth curved surface. Only six students managed to perform the task accurately by drawing a tangent and a normal at the point of incidence.

Sixty three percent of students did not know how to use ray drawings to determine the position of an image in a plane mirror. Figure 2.5 shows the various methods used by students in determining the image position for reflection in a single plane mirror. Only 15 out of 41 students were able to use geometrical ray drawing, to accurately determine the image position.

Students were unable to determine the number of images formed for two plane mirrors: inclined at an acute angle to each other; and placed parallel to each other.

For two mirrors inclined at an angle to each other, many students used the formula $n=360/\theta - 1$ to determine the number of images formed. None were able to

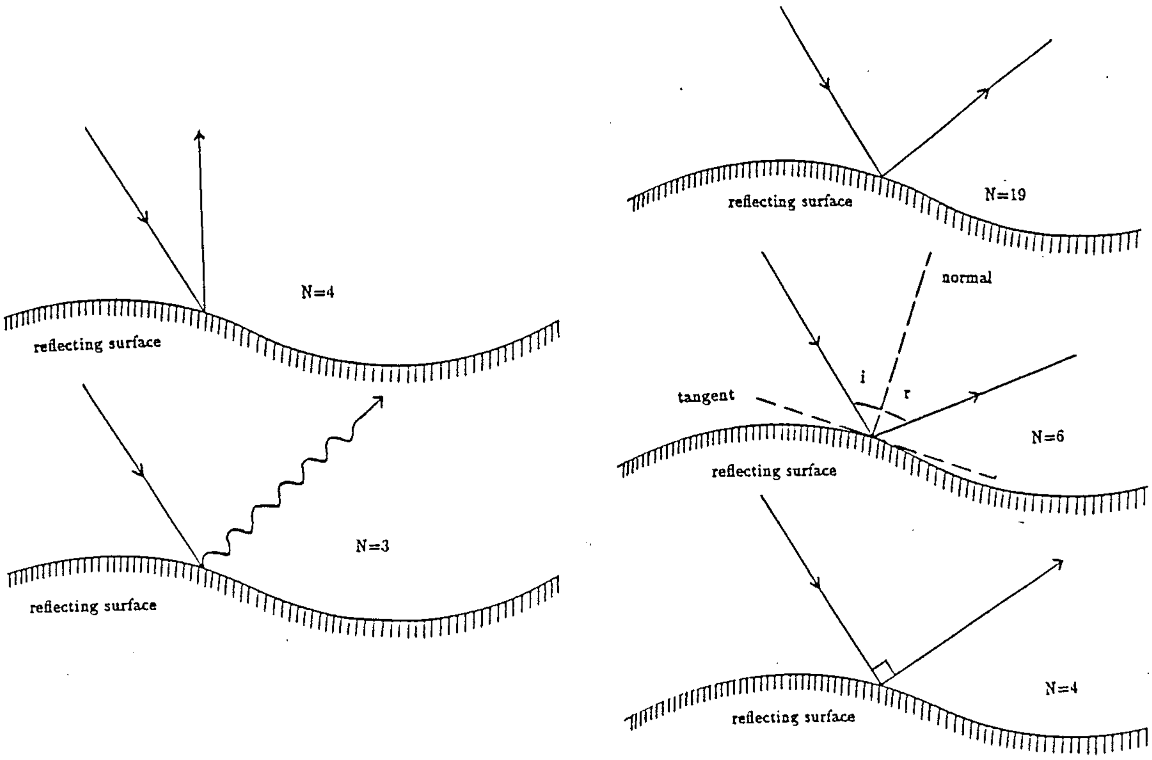

Figure 2.4: Rays drawn for reflection off a smooth curved surface ($N_{Total} = 42$).

determine the positions of the images formed in the two inclined mirrors (see figure 2.6). For two parallel mirrors, 16 out of 42 students knew that an infinite number of images would be formed. Only 2 of them could support their answer by using ray tracing (see figure 2.7).

For curved mirrors, students used specially produced, standardized rules for determining image positions. For example, incident rays parallel to the principal axis will be reflected through the focus and vice versa. Many did not realise that the laws of reflection were being applied.

The Form six group of students performed quite well in determining the position of an image in a curved mirror (see table 2.4) as they were studying that topic in class during the administration of the questionnaire. However, seventh formers in the same school, who had studied the topic the previous year with the same teacher, did not fare as well, indicating poor recall and retention.

2.4 State of Knowledge of Students

The study highlighted the following facts about the state of knowledge of students: the tendency to classify subject matter by content; a surface understanding of the content learnt and a lack of ancillary knowledge.

They had difficulty in retrieving, relating and applying the ideas learnt. On numerous occasions they were unable to provide explanations in support of their

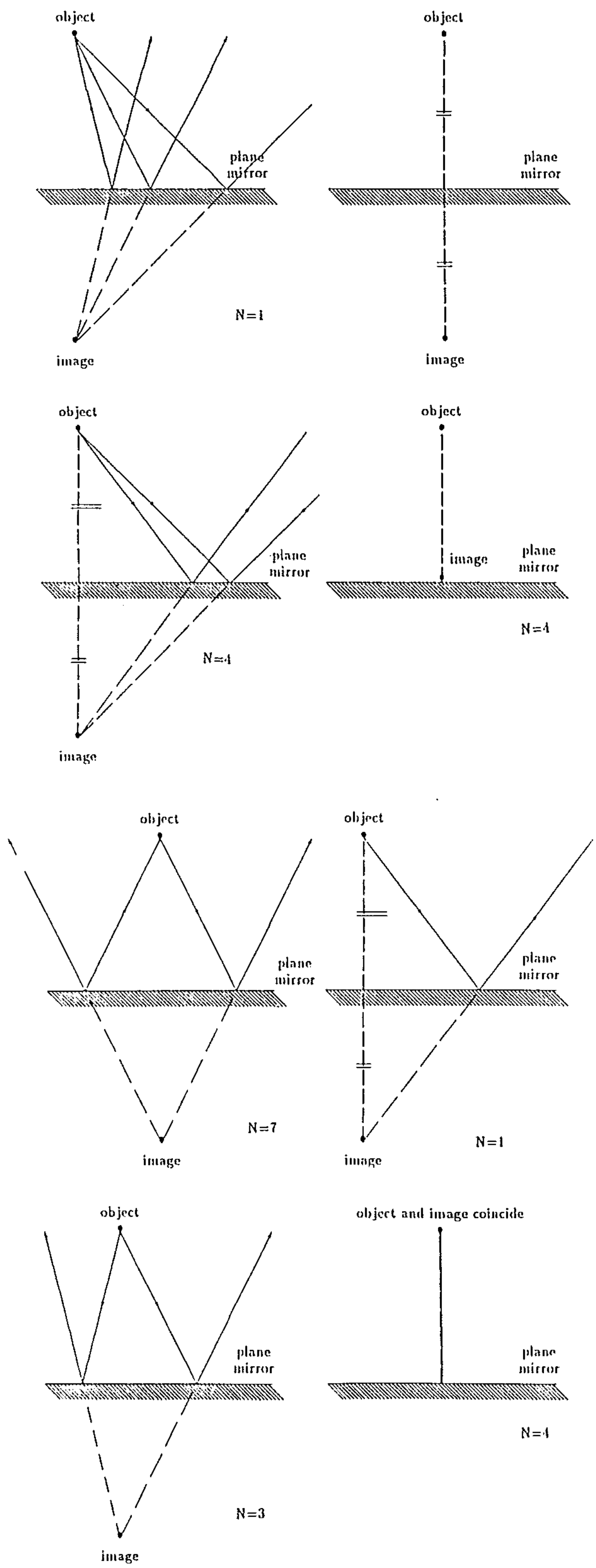

Figure 2.5: Images drawn for a plane mirror ($N_{Total} = 42$).

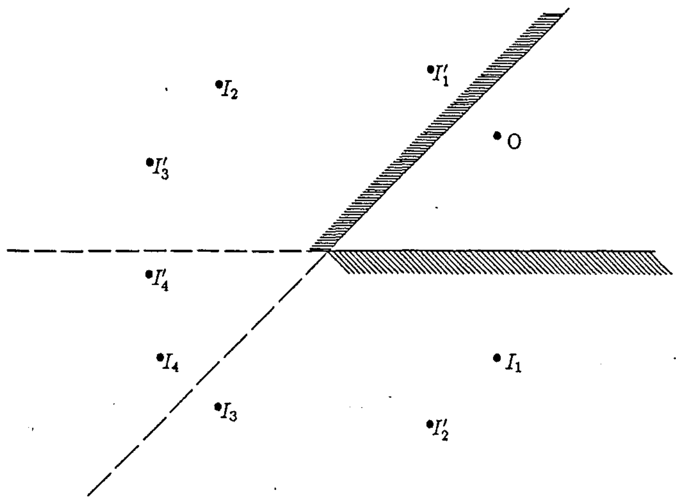

Figure 2.6: Image positions for two mirrors inclined to each other.

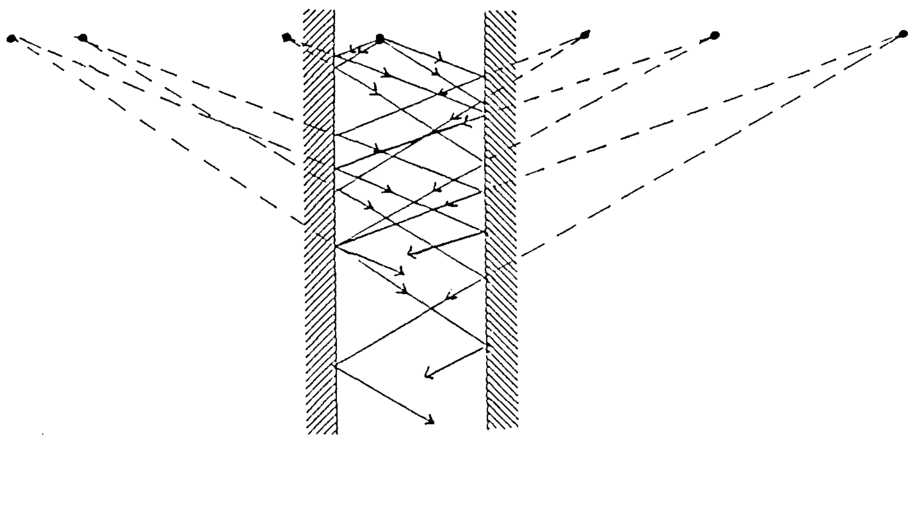

Figure 2.7: Ray drawing to determine the image positions for two plane parallel mirrors ($N_{Total} = 42$).

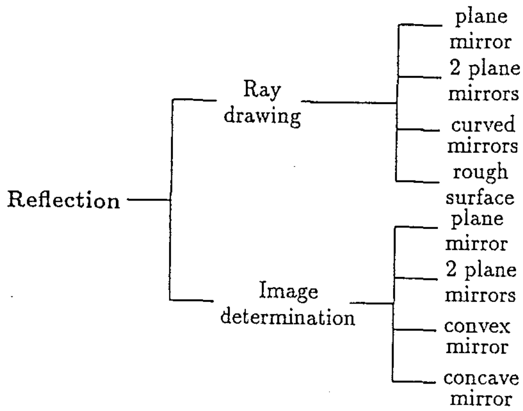

Figure 2.8: Reflection classified as 8 broad content groups.

answers.

2.4.1 Classification as content

To many students the basic propagation and reflection of light are each a conglomeration of independently existing topics. They use surface features to categorise the content learnt. Structure 2.1 shows the classification of reflection into eight broad content categories. These are further subdivided to form 21 content groups, shown in structures 2.2 and 2.3. This was evident from the answers provided by the students. Students create these content categories to simplify and make sense of the knowledge learnt. The content categories used by students are similar to the classifications used in many textbooks.

Students were given slightly differing tasks requiring the application of the same principle. In many cases they were able to apply the principle to one situation but were unable to extend its application to the other cases. When faced with a certain problem (or situation), they were able to answer if it fitted a content group in their minds. To them, there exist as many topics as there are examples with different surface features. Very few were able to generalise and apply the idea learnt. Examples where content classification was apparent are image formation using pinholes; ray tracing for reflection off plane mirrors; image determination in plane mirrors; and image determination in curved mirrors;

2.4.2 Surface Understanding

In many of their answers, students hinted of knowing the subject matter but failed to provide a fitting explanation. The answers provided showed a shallow understanding of the subject matter. Surface understanding was portrayed in explaining: the nature of light; the formation of a shadow; the blurring of an image due to a larger pinhole; the brightness of images formed by one and two pinholes; the terms principal focus, convex and concave mirrors; and the observance of non luminous objects.

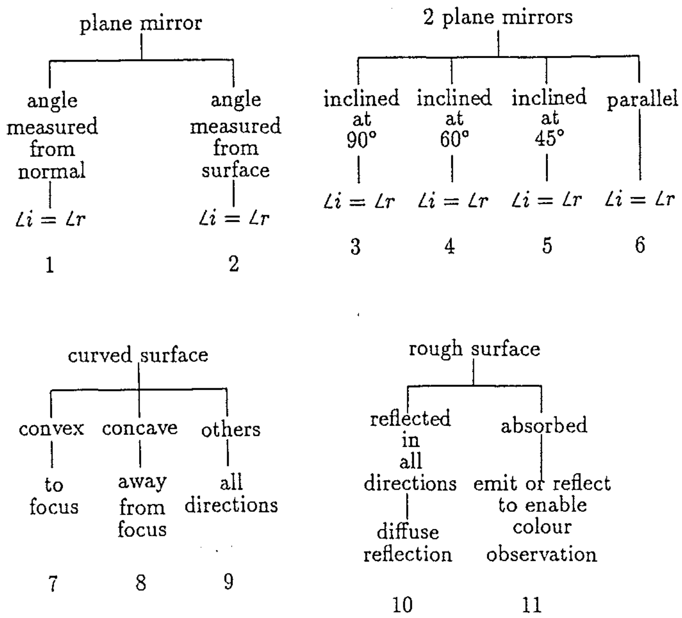

Figure 2.9: Content categories for ray tracing.

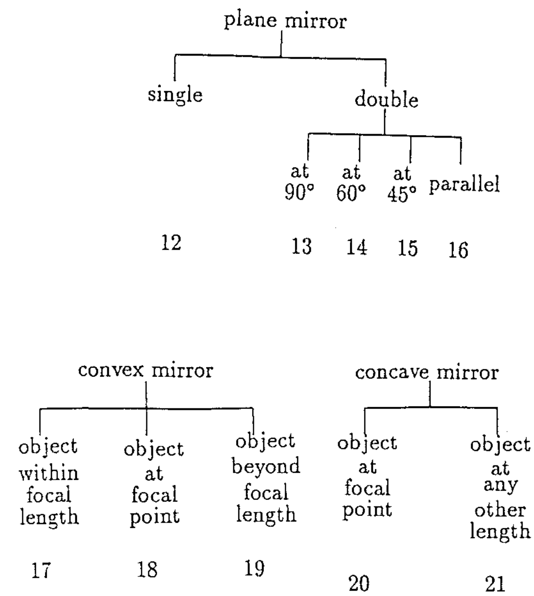

Figure 2.10: Content categories for image determination.

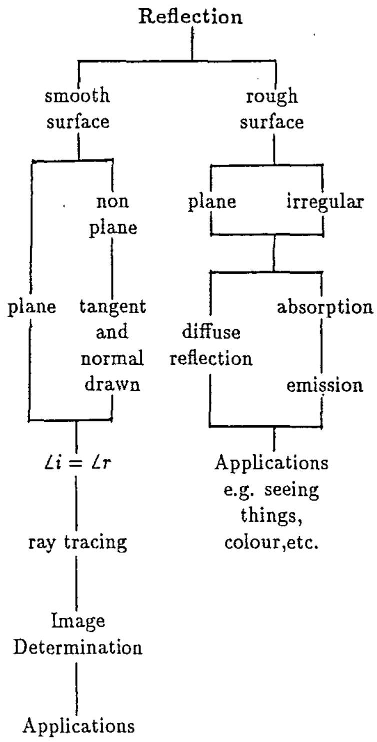

Figure 2.11: Reflection as a concept.

2.4.3 Ancillary Knowledge

In quite a few instances, students knew the rules and the phenomena but could not provide the conditions of its applicability. This was portrayed in explaining the law of reflection; diffuse and regular reflection; and ray tracing for reflection off different smooth surfaces.

Table 2.3 shows that every group scored markedly higher in stating the meaning of the symbols for the equation governing the law of reflection in comparison to stating the conditions of its applicability. They knew that $\angle i = \angle r$ was the law of reflection but few knew that the incident ray, the reflected ray and the normal at the point of incidence must lie in the same plane; it is applicable to any smooth surface; and the angle should be measured from the normal

They associated reflection mainly with plane mirrors and had difficulty in generalizing its application to curved surfaces. They generalized the law of reflection to diffuse reflection stating that $\angle i = \angle r$ for both cases.

In studying the law of reflection, students lacked the knowledge that it was for image observation. They did not realise that it was not applicable to observation of all things around us. Reflection in two plane mirrors and curved mirrors were treated differently. Special rules were used for image observation in each. Students seemed to learn the rules but they were unable to relate reflection to actual phenomena, except in the case of plane mirrors. Due to a lack of ancillary knowledge, they were unable to answer questions that required the combination of information.

2.5 An Alternative Teaching Approach

Studies (e.g. Viennot 1979 and diSessa 1982) have shown that students construct views of natural phenomena and bring them into the classroom. Students use intuition to make sense of the world around them and this sometimes results in misconceptions of the physical phenomena. It follows that understanding, ancillary knowledge and conceptions that students have prior to instruction, need to be determined and taken into consideration in our teaching. Simple questionnaires suffice for this purpose and could be readministered, to determine the amount of learning and correction that has taken place.

We suggest concept teaching to change the content categorised thinking of students. Bruner et al (1977) sees any concept as having a name; examples (positive and negative); attributes (the common features or characteristics that cause us to place examples in the same category); and a rule. We have proposed a conceptual framework for reflection (see structure 2.4). Content learnt may be classified within this framework using the associated rules. The framework may be modified to encompass any new related content learnt.

In our attempt to simplify the subject matter for the students, we isolate and teach it. This can result in it being alienated from real life situations, as in the case of reflection with mirrors. Students learn reflection for image formation but observation using diffuse reflection is neglected. Lessons are commonly started with opening statements such as *Today we are going on to concave mirrors.* This creates content classification in the minds of the students. Labels for content cannot be avoided but may be minimised. It is comon practice for textbooks to classify by content. The topic could be introduced by saying *Today we are going to learn how the principles of reflection apply to concave mirrors.* The rules for reflection should be used to determine the images, and similarities with image determination in plane mirrors emphasised. At present image determination in curved mirrors is taught without relating it to the central concept of reflection. In using ray drawing to teach it, standardized instructions are commonly given in textbooks and classrooms. For example, Halliday and Resnick (1988 p876) state:

We can locate an image of any off axis point graphically by tracing any two of four special rays. Thus:

1. A ray that strikes the mirror parallel to its axis passes through the focal point.
2. A ray that strikes the mirror after passing through the focal point emerges parallel to the axis.
3. A ray that strikes the mirror after passing through the centre of curvature returns along itself.
4. A ray that strikes the vertex of the mirror will be reflected at an equal angle with the axis of the mirror.

Note that except for the last statement, no mention of reflection is made. This implies that only rays from the tip of the object are taken and the base of the image is assumed to lie on the principal axis (see figure 2.8). We argue that rays need to

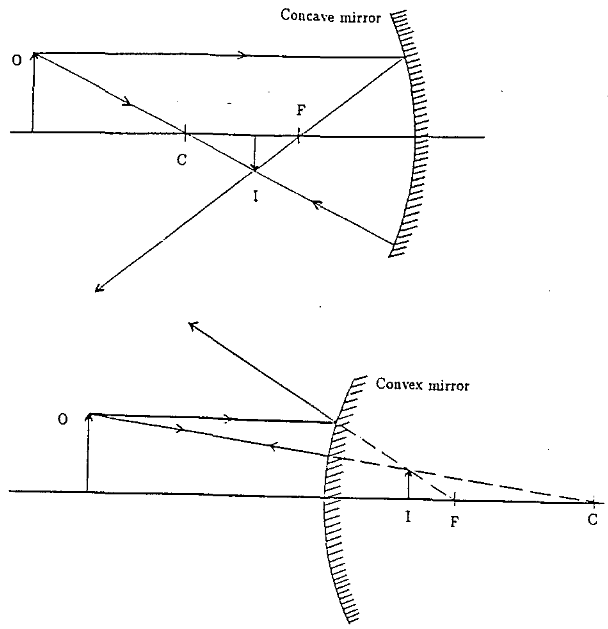

Figure 2.12: Standard steps for image determination in spherical mirrors.

be taken from the base of the object as well, to show that its image will lie on the principal axis. Teaching standardized procedures for concave and convex mirrors results in their being separately learnt and hence becoming independent cases.

Students need to be constantly reminded that reflection is involved. Image determination could be performed for a point object and then a line object. The procedure is then easily generalised to an object of any shape. The procedures should be repeated for different positions of the object. Standardized rules to determine the image position should not be used until the student has understood and internalized the concept. An alternative set of instructions is outlined below:

1. Recall the application of the law of reflection in determining the image position in a plane mirror;

2. Draw two rays from any point on the object incident on the surface of the mirror (see figure 2.9). Determine the centre of curvature of the surface (if it is curved). Draw a normal at each of the two points where the rays are incident on the mirror.

3. Applying the law of reflection, accurately draw the path of the reflected ray for each of the incident rays. The point at which the rays intersect is the image position. If these rays do not meet, obtain the position of a virtual image by extending the rays back.

4. Draw rays from different points of the object to show that any point on the object may be used keeping in mind the role of the extreme points of the object in obtaining the outline of its image.

Chase and Simon (1973a,b) have shown that chess experts have a repertoire of patterns. They use these patterns to first determine a few alternatives. They then use the subject matter knowledge to test the alternatives thoroughly. They then discard poor ideas and pursue good ones. Similarly, students should be taught a

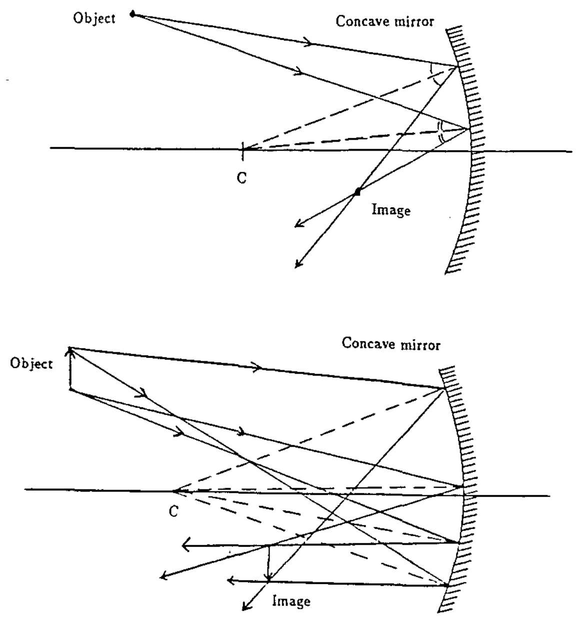

Figure 2.13: Using the law of reflection to determine the image position in a concave mirror.

repertoire of possibilities for image determination from which they may choose those that provide an efficacious solution.

At present, students are confused and unsure when tracing rays reflected off smooth, non-plane surfaces. They roughly know the direction of the reflected ray but do not know how to accurately draw the path of the ray. Exercises performed in class do not normally require accurate drawing. Rough sketches are usually accepted.

Once the case of one mirror has been learnt, the procedure may be extended to two or more mirrors. Students should be taught to relate reflection off any smooth surface to the familiar case of reflection off a plane mirror. Like chess experts they will then realise the patterns. Short cuts might make it simpler but it also breaks the continuity of general thought and connection. Learning by concept enhances recall and application to new situations. The ancillary knowledge of the laws needs to be ingrained for students to fully understand the applicability of the concept in different environments.

The discussion has concentrated on regular reflection. Diffuse reflection may also be treated in a similar manner. Structure 2.4 gives a way of encompassing the two processes and treating them as a single concept. The structure showing the connection of content to the central concept should be kept simple. We are of the opinion that: students will be able to learn and use it, if it has a simple longitudinal flow; and too many lateral connections causes confusion and might encourage content learning.

2.6 Conclusion

It seems that there is a general applicability of knowledge structure within the learning process. Our study in Optics has shown student conceptions and knowledge structure is similar to those found in studies of student conceptions in Mechanics and in Electricity. We have been able to trace these conceptions to a lack of ancillary knowledge; a surface understanding of the subject matter learnt; content teaching and learning; and style used both in the student textbooks and in the texts consulted by teachers. All this encourages students to use surface features to classify knowledge learnt into content groups. Few students recognised that common principles of reflection were common to all content groups. Many students are unable to see, much less appreciate, the simplicity and orderliness of scientific explanations.

Much is now known about how students think and the meanings various words hold for them. In order to affect the conceptions of students, their prior knowledge structure has to be taken into account. A conceptual knowledge structure has been developed for reflection. We have proposed a modified approach to the teaching of reflection that links the key concept to the full range of situations. The future will show whether this approach enables students to develop the appropriate conceptual knowledge structure.

Chapter 3

Refraction: Conceptions and Knowledge Structure

3.1 Introduction

Geometrical optics features as a major component in high school science (Bowden et al, 1972; Castle, 1986 and University Entrance Board, 1989) but many students do not seem to fully comprehend the processes of reflection and transmission (refraction)(Singh and Butler, 1989a). Many students do not even realise that a light beam incident at an interface between two media, is partially reflected and partially transmitted. Only reflection or refraction is considered each time. This conception may be traced to the isolation of the topics in trying to simplify the teaching and learning process. Textbooks briefly treat reflection and refraction together in the introductory stages after which each is separately treated in detail.(e.g. Ohanian, 1985 p831 and Halliday & Resnick, 1988 p988).

Studies of student conceptions and state of knowledge in optics have been reported for the propagation of light (Stead and Osborne, 1981); reflection (Guesne, 1981 and Jung 1981); and images formed in convex lenses (McDermott, 1987). These studies have found that students have certain conceptions that are not in line with the standard theories of light.

Chi et al (1981) showed that for problem solving in mechanics, novices categorise problems using surface features as opposed to the experts who categorise using broad physical principles. We have previously shown that students develop a knowledge structure of reflection characterised by their surface impressions of the situation and not the underlying concepts of reflection (Singh and Butler, 1989b). In this paper we study the students conceptions and knowledge structure of refraction, and find that it is also a conglomeration of independently existing content groups.

The optics knowledge learnt in high schools and the first university year is elementary enough to enable an insight into the conceptual knowledge framework of students. In section two, we use eight examples of the refraction of light to determine the state of knowledge and conceptions of students aged 15-18 years. In section

Questionnaire	Description	No. of Students
Terms	Terms used in refraction	35
Equations	Equations used in refraction	35
Refraction	Refraction at plane and curved interfaces 37	
Reflection	Refraction and reflection at plane surfaces	45
Lenses	Refraction in lenses	42
Prisms	Refraction in prisms	41

Table 3.1: Questionnaire description.

Group	Description	Age	Number
Form 5	Form 5 students from two schools in New Zealand	15 yr	39
Form 6	Form 6 students from two schools in New Zealand	16 yr	43
Form 7	Form 7 students from two schools in New Zealand	17 yr	39
S'pore	Pre-university 1 students from two schools in Singapore	16yr	36
NZ	First year New Zealand undergraduates reading physics	18yr	8
Foreign	First year foreign undergraduates reading physics in New Zealand	18yr	5

Table 3.2: Student groups who participated in the study.

three we use this information to formulate the knowledge structure of these students and to propose a conceptual framework for the teaching of refraction.

3.2 Conceptions in Refraction

Six sets of questionnaires (see table 3.1), were administered to six different groups of students (see table 3.2) over a period of six weeks, prior to the optics teaching for that year. Each questionnaire consisted of short structured questions. Although no time constraint was applied in administering the questionnaires, none of the students took more than an hour to complete each. Students were interviewed wherever clear and direct inferences could not be made from their answers. Only short and simple questions were used. Diagrams were provided in many instances to provide clarity.

The six questionnaires were uniformly distributed within each group for the form 5, form 6, form 7 and Singapore student groups. Each student in the New Zealand and Foreign student groups answered all the questionnaires. Students chosen were from schools that had geometrical optics as part of their school syllabus. All the undergraduates participating had studied geometrical and wave optics in senior high school.

The form 5 students scored the lowest in every questionnaire. Although the syllabus prescibes that some aspects of geometrical optics be taught during the form 1 to form 4 years, their conception and understanding of refraction was low. In many instances, even when students knew the answers they could not provide an explanation, showing a superficial understanding of the subject matter. For all the questionnaires students scored lowly in questions requiring the application of principles to non-standardized situations. They performed well in standard type questions used as examples in the classroom and in textbooks. First year physics undergraduates did not perform significantly better than any of the other groups, excepting the form 5 students group.

Some examples from the study are discussed to show the conceptions and content classification of students. Due to a surface understanding and a lack of ancillary knowledge students use surface features to classify content learnt into independently existing groups.

Example 1

Students were asked to explain the terms *Refraction* and *Refractive Index*. Eighty two percent of the students explained refraction as the bending of light incident at an interface between two media. Only 2 out of 35 students mentioned that light at normal incidence at an interface would be refracted. These students explained refraction using the change in speed. The others did not consider it at all or thought that at normal incidence refraction did not take place.

Only 4 out of 35 students defined refractive index as the ratio of the velocity of light in vacuo to the velocity of light in a medium. Out of 29 students who knew the term refractive index, 14 used the formula $n = \sin i / \sin r$ to define it.

Example 2

Students were asked to complete the path of a ray incident at a plane interface by considering *all the possible directions of the rays.* Eighty eight percent did not consider reflection stating that only refraction would take place as the rays were not incident on mirrors. Students are of the impression that the ray is either reflected, refracted or absorbed. They gave textbook answers where only one process is usually considered each time (e. g. Bowden et al, 1972 and DeCourcy & Epp, 1982). In teaching, the three processes are usually separated and taught independently. In ray drawing exercises, the students are usually expected to consider only one process at a time.

Example 3

Students were required to complete the path of rays incident on a set of curved surfaces. From figure 3.1, it is obvious that many students were unable to do so. Those who drew near correct sketches were asked to make accurate drawings. Only 4 of them were able to do it although 78% could draw the path of a ray refracted at a plane interface. Many diverged or converged the rays whenever faced with parallel rays incident on a concave or convex surface (see figure 3.1a,b,c). They applied the rules used for parallel rays refracted in lenses.

For the sphere silvered on one half (figure 3.1d), the rule of converging or diverging rays was not applied when only one ray was given. Only 7 out of 37 students accurately completed the path of the ray. When more rays were drawn to form an incident beam of parallel rays, 5 of these 7 students stated that the rays would converge to the centre of the sphere or to some point on the diameter of the sphere.

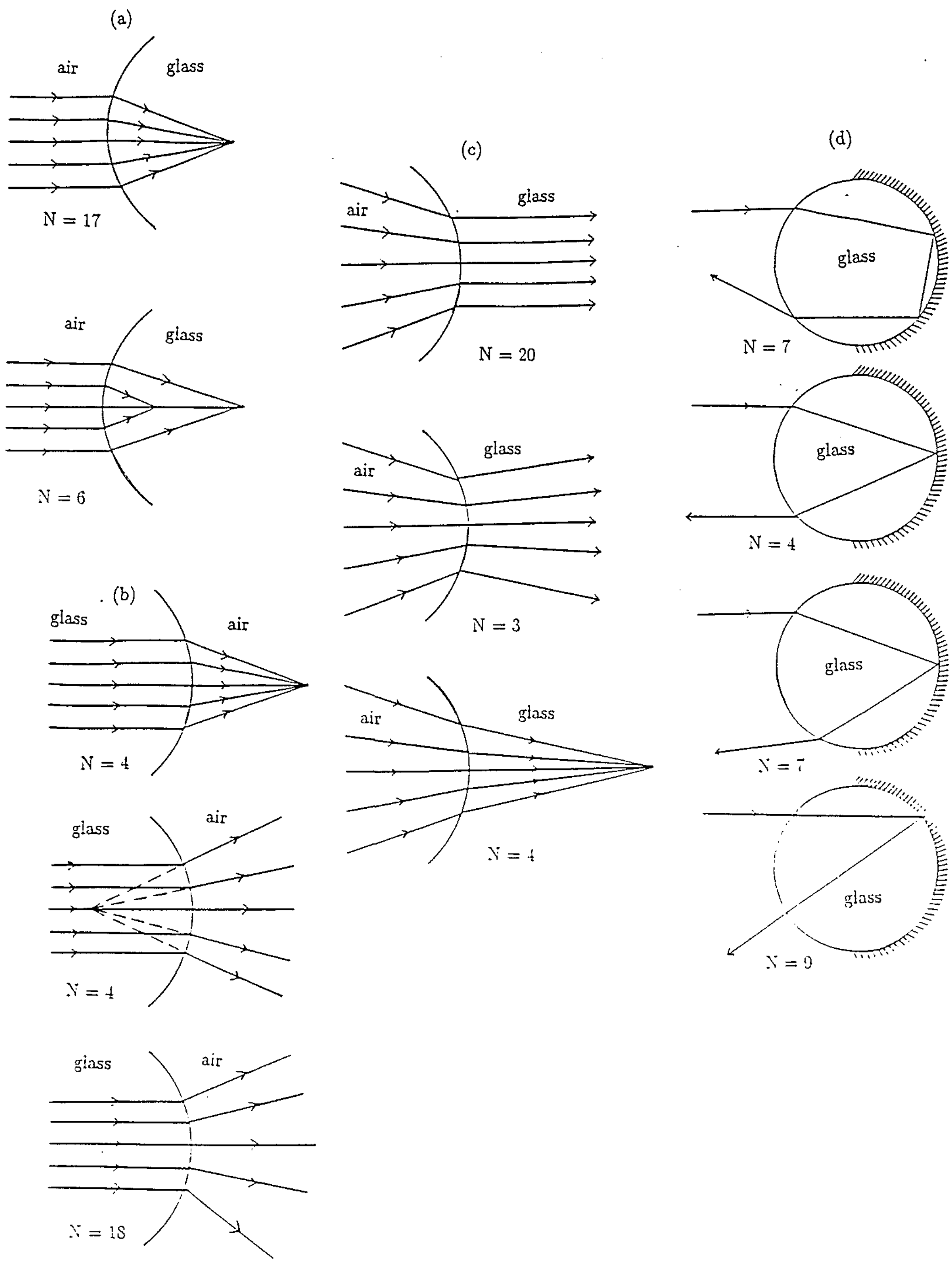

Figure 3.1: Students' responses for rays incident on curved surfaces.

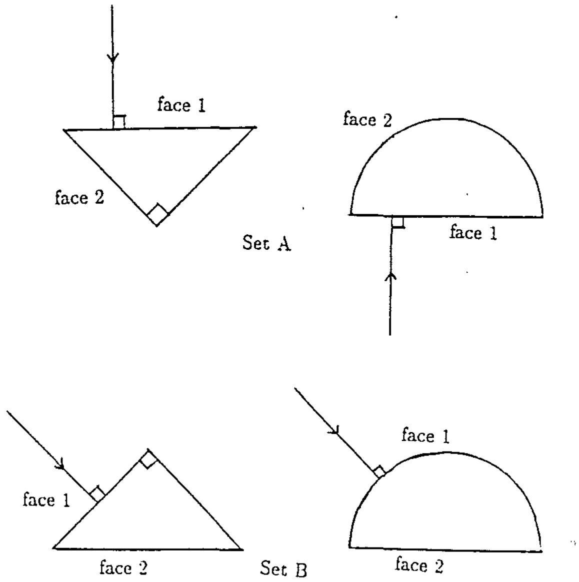

Figure 3.2: Two configurations of a prism and a semi-circular glass block.

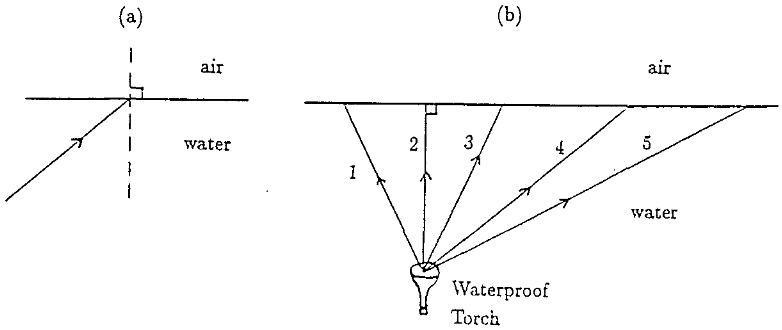

Figure 3.3: Configuration to test conceptions on total internal reflection.

Examples of the rough sketches drawn by most students are given in figure 3.1.

Example 4

Students were given two sets of diagrams (see figure 3.2) of a right angled isosceles prism and a semi-circular glass block. For each set, the ray was drawn such that for both the prism and the semi-circular glass block: it would be incident on the second face at exactly the same angle; the ray would traverse exactly the same path; and the angle at which it would be incident at the second face would be larger than the critical angle.

A large number of students drew the rays totally internally reflected for the prisms (see table 3.3). The students did not bother to check the magnitude of the incident angle at the second face to test for the possibility of total internal reflection. They could not explain why the ray would be totally internally reflected. For the semi-circular glass block, very few drew the ray as totally internally reflected (see table 3.3). Furthermore, for the prisms everyone gave some form of ray drawing but for the semi-circular glass block, 9 for set A and 7 for set B did not know how to commence the task. To them prisms indicated the possibility of total internal

Path of ray completed by showing	Set A		Set B	
	Prism	Block	Prism	Block
refraction at the first face	5	9	3	8
refraction at the second face	5	14	5	22
total internal reflection	31	9	33	4
inability to commence the task	0	9	0	7

Table 3.3: Students' responses for the prism and semi-circular glass block configurations of figure 3.2.

reflection while the semi-circular glass block represented refraction. Textbook and classroom exercises usually feature prisms for showing total internal reflection. Semi-circular glass blocks are usually used to show refraction effects.

Example 5

Students were given two different configurations to determine their conception of refraction for rays incident in a denser medium. For figure 3.3a, a ray was drawn at an angle of incidence greater than the critical angle. Sixty two percent of the students drew the ray refracted into the lighter medium. Of the 5 out of 37 who drew the ray totally internally reflected, 2 thought that refraction from a denser to a lighter medium took place for very small angles of incidence.

In the second case (see figure 3.3b), a series of rays were drawn at varying angles of incidence. The angles of incidence for rays 4 and 5 were drawn greater than the critical angle of the medium. For ray 4, only 3 out of 37 drew the ray being totally internally reflected while for ray 5, 11 did so. Some students even refracted ray 2 which was at normal incidence. Ray 1, was drawn forming an angle of incidence slightly lesser than the critical angle. Of the 23 who drew it refracted, only 6 stated that the angle of incidence was less than the critical angle of the medium.

Students have a very poor conception of the conditions necessary for total internal reflection. Unless the angle of incidence appeared very large, most students did not consider total internal reflection. They lacked a knowledge and understanding of the finer details needed.

Example 6

Students had to complete the path of a ray of sunlight incident on the face of: an equilateral prism; and a set of two equilateral prisms with one inverted (see figure 3.4). Seventy percent of the students could complete the path of a ray: incident at a plane interface; and refracted in a medium with plane, parallel faces. For prisms,

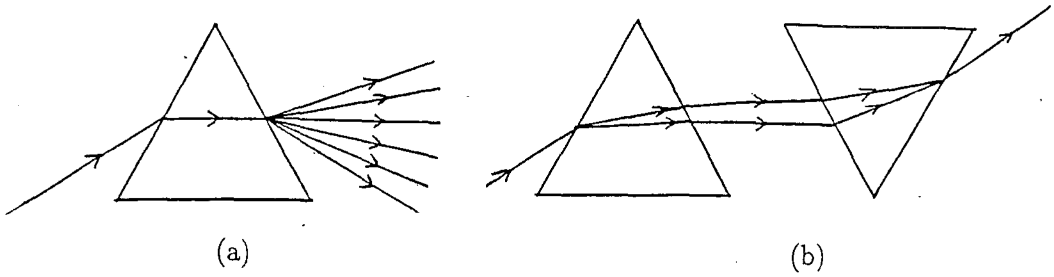

Figure 3.4: Completing the path of a ray of sunlight through prisms.

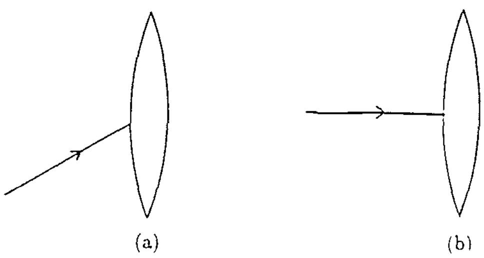

Figure 3.5: Ray incident at the centre of a thin convex lens (a) at an angle to the principle axis and (b) parallel to the principal axis.

they were able to draw the refraction of the incident ray at the first face. They faltered when drawing the refraction of the ray at the second face. Fourteen percent drew the emergent ray parallel to the incident ray for figure 3.4a.

Only 37% drew the dispersion effect correctly. Thirty four percent drew it at the second face of the prism, as the ray exited the prism. Twenty two percent contradicted the law of refraction (see figure 3.4a). Many considered dispersion as totally different from refraction and not as the resulting effect. To them dispersion supercedes refraction in prisms.

For figure 3.4b, 32 out of 41 students did not show recombination of the rays. Seven of them refracted the rays the same way in the inverted prism as in the upright prism thus producing a greater dispersion. Only 9 were aware that an inverted prism reverses the dispersion effect caused by the upright prism. Students who could show the refraction of the rays correctly for plane interfaces, incorrectly drew the refraction of the rays in the inverted prism.

Example 7

Students were given a ray incident at the centre of a thin lens: at an angle to the principal axis; and along the principal axis. For figure 3.5a, 71% of the students deviated the ray from its incident direction. Of the 12 students who drew the ray emerging parallel to the incident ray, only 4 showed the refraction of the ray in the lens. The others drew it passing straight through without showing any refraction effects. For figure 3.5b, 98% drew it passing through without deviation. When determining the position of images formed by convex and concave lenses, practically all the students drew a ray passing undeviated from the tip of an object through the centre of a lens. Yet when given the task of figure 3.5a, very few could complete

Ray diagram	Convex lens			Concave lens		
	$u > f$	u = f	$u < f$	$u > f$	u = f	$u < f$
Correctly drawn	27	18	17	14	12	10
Wrongly drawn	8	16	16	15	17	15
Could not do it	7	9	10	14	14	17

* u: object distance from the lens
* f: focal length of the lens

Table 3.4: Students' performance in using geometrical ray drawing to determine image formed by a lens.

the path of the ray correctly.

Example 8

Students were required to perform geometrical ray drawing to determine the position of an image formed by a lens. A line object was placed on the principal axis at different distances from: a convex lens; and a concave lens.

Students knew that parallel rays incident on a lens: converge to the focal point for a convex lens; and appear to diverge from the focal point for a concave lens. They knew that a convex lens usually forms a real and inverted image while a concave lens forms a virtual, upright and diminished image. Table 3.4 shows that only in the case of $u > f$ for a convex lens did students perform the task quite well. Of the 18 students who drew the ray diagram correctly, for u = f: 4 stated that the image was formed at infinity; 10 stated that no image would be formed as the rays were parallel; and 4 of the students could not explain where the image would be formed. For a concave lens, although exactly the same procedure was required, fewer students knew how to determine the image position

Students perceive each case of image determination as a distinct case. Each object distance is considered as a totally different situation. The similarities between the six cases in table 3.4 as perceived by the students are: lenses are involved; a line object placed on the principal axis is being used; and image determination using geometrical ray drawing is to be performed.

They do not perceive image determination as a singular theme similarly applicable, irrespective of: the position of the object from the lens; and the nature of the lens. Many do not consider lenses to be a part of refraction. They perceive lenses as a topic governed by a different set of rules from refraction.

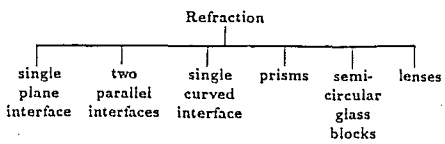

Figure 3.6: Refraction perceived as six broad, independent, content categories.

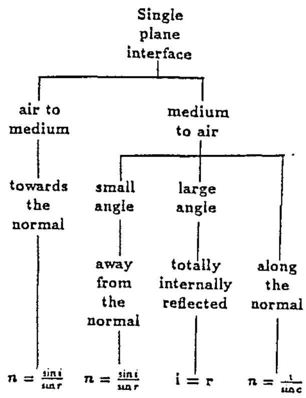

Figure 3.7: Students' knowledge structure for refraction at a plane interface.

3.3 Knowledge Structure

To students, refraction is a conglomeration of independently existing topics categorised into groups using surface features. These categories are not considered connected by a central concept but exist as independent groups. The only similarities perceived by the students are those governing the surface features.

Shavelson (1973a,b) reports how learners acquired knowledge structures which the teacher or the text presents. In our study, the students' answers confirm this type of knowledge structure. Structure 3.1 gives 6 broad categories encompassing the surface features of the shapes used in the questionnaires. The categories increase with the number of shapes used. Many teachers and texts use such categories when teaching refraction. Students use surface features to further subdivide this knowledge structure into content groups. Structures 3.2 to 3.7 show the surface features used by students to structure the subject matter learnt into 44 content categories. They try to simplify the complexity of the subject matter by structuring it into small content groups of a single surface feature. For each of the categories shown, not all the students would descend to the final stage. For example, in the first category in structure 2, some of the students may only be aware that the ray is refracted towards the normal for refraction from air into another medium. Not all the students may have knowledge of the formula $n = \sin i/\sin r$. The same category may be created but the level of information within it varies with the knowledge level of the student.

General rules and principles are rarely used to classify the content learnt. For spherical surfaces refraction is not considered (see structures 3.4 and 3.7). Even when a similar object is drawn at a different orientation on the page; or the orientation of the incident ray with respect to the object is changed (see structure 3.5), students tend to treat it as a different category altogether. Any slight change in the surface

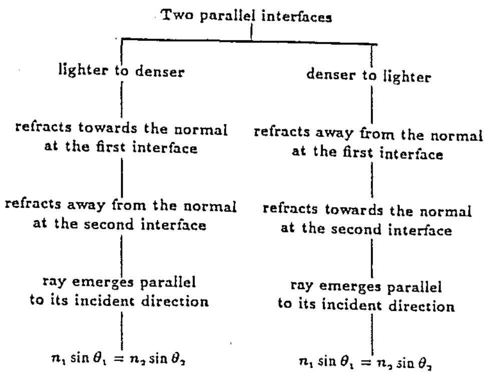

Figure 3.8: Students' knowledge structure for refraction at two parallel interfaces.

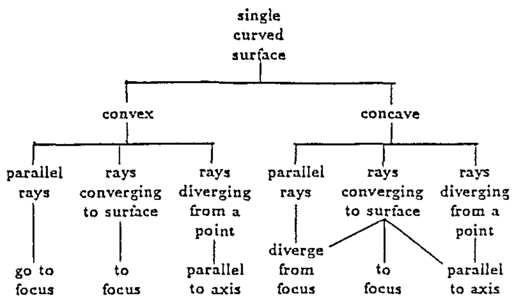

Figure 3.9: Students' knowledge structure for refraction at a curved surface.

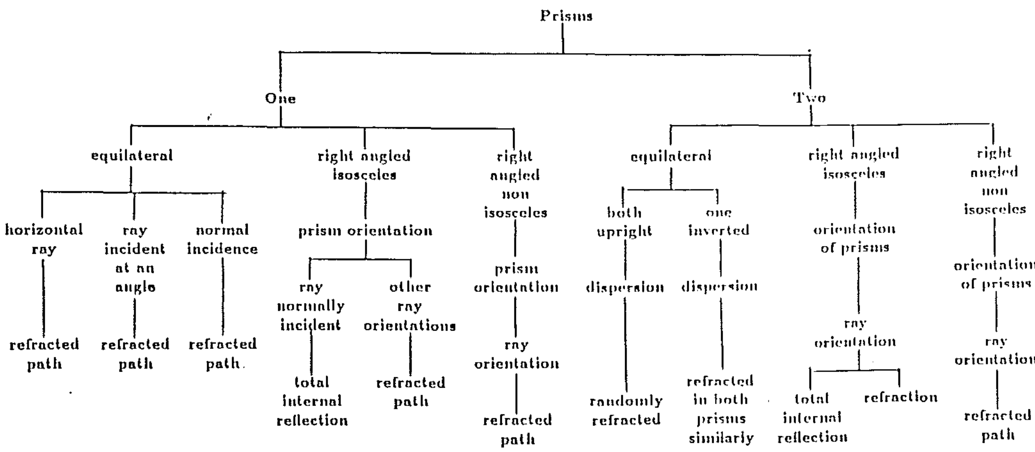

Figure 3.10: Students' knowledge structure for refraction in prisms.

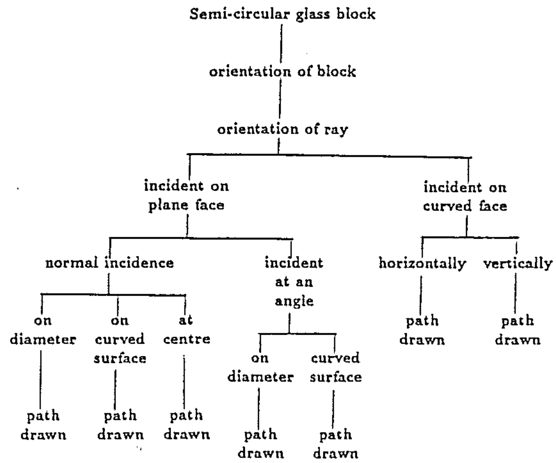

Figure 3.11: Students' knowledge structure for refraction in a semi-circular glass block.

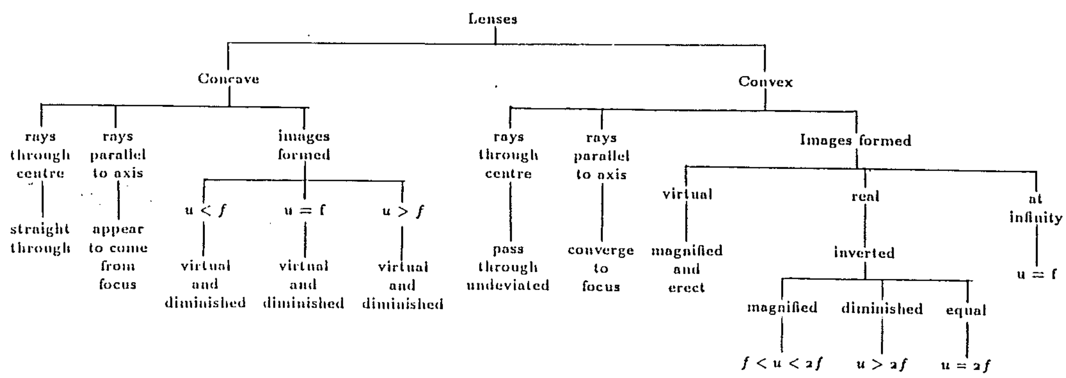

Figure 3.12: Students' knowledge structure for refraction in lenses.

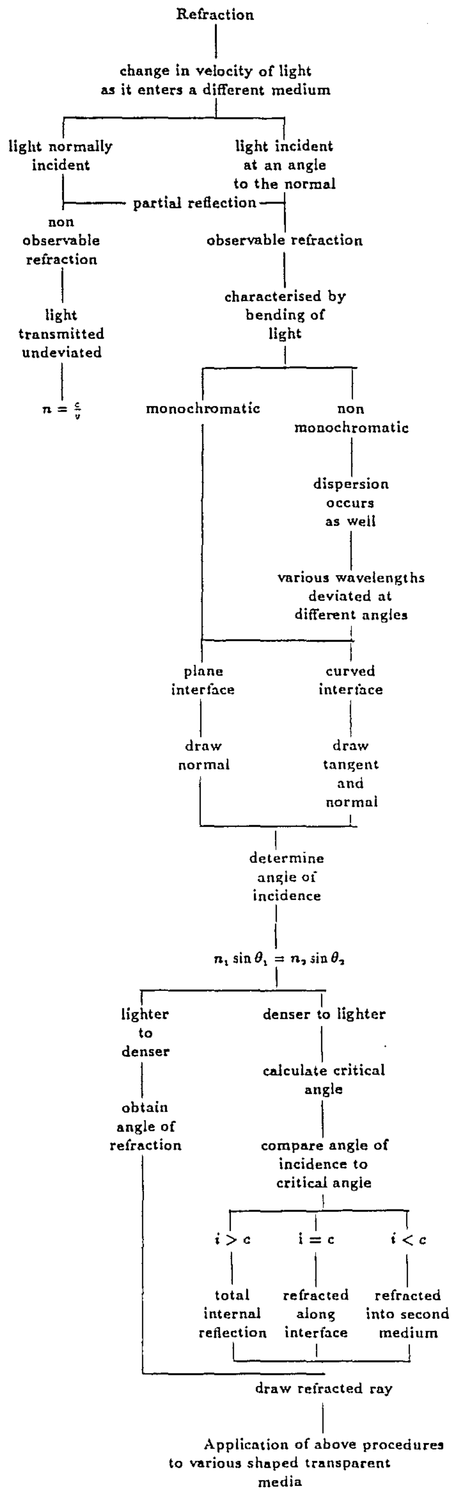

Figure 3.13: Refraction as a concept.

feature of a configuration causes the students to categorize it differently. This was evident from the different answers to questions requiring the application of a similar principle. When faced with a certain set up, students were able to answer only if the configuration exactly fit a specific content group within their knowledge structure.

Instruction should emphasise the organisation of the subject matter. Students need to be made aware of the connections between the various content groups and taught to classify conceptually, using rules, principles and ancillary knowledge. Structure 3.8 has been proposed to show a possible organisation of the various topics within the single concept of refraction. Students could be taught such a knowledge structure and its application to problem solving. A wide variety of examples need to be given, to ingrain the structure and its usage in the minds of the students. This will hopefully enhance concept learning amongst the students. The structure developed, should be treated as a dynamic system and constantly reviewed and updated to encompass newly acquired and related content.

3.4 Conclusion

Our study has shown that for refraction the knowledge level of our sample of first year undergraduates is essentially at the same conceptual level as that of the high school students. Subject matter is being learnt as a conglomeration of independently existing content groups. Content teaching and learning, at the expense of conceptual frameworks, has resulted in a lack of proper knowledge structure amongst students. Content covers a wide range but insufficient depth. Students know the subject matter superficially but are unable to provide explanations. Many of the conceptions of the students arise because of a lack of depth in knowledge and organisation of the subject matter learnt. Students try to generalise the subject matter learnt but lack the ancillary knowledge. Consequently, situation specific rules are learnt. Lenses is an example of a topic highly categorised by textbooks into content groups using situation specific rules (see structure 3.7). It is not taught as part of the concept of refraction but as an independent topic governed by its own special rules.

The answers of students have been used to formulate their knowledge structure. It closely resembles the classification used in textbooks. A conceptual knowledge structure encompassing all the content categories used by the students has been proposed. This may be used to show the organisation of the content learnt, to modify the knowledge structure of students to portray the orderliness and analytical thought which characterises science, and to help in developing a problem solving technique for students. Science curriculum in schools needs to include not only a conceptual subject matter approach but subject matter organisation as well, in order to modify the conceptions of students. Use of the conceptual framework proposed here will determine its effectiveness in modifying the knowledge structures of students.

Chapter 4

Effect of Knowledge Base on Conceptions in Mechanics

4.1 Introduction

Since the 1970's much research has been done to determine the conceptions of students in mechanics (see review article by Gilbert and Watts, 1983; and Halhoun and Hestenes, 1985). These studies have discussed and highlighted the conceptions of students on motion, gravity, force and energy. They have shown that these conceptions are not in line with the general theories of classical mechanics, that students acquire these conceptions through daily experience prior to instruction and formal instruction in physics does not have much effect in changing these conceptions. Students of various age groups up to the first university year of study have been observed.

The studies have however, not tried to trace the age or academic level beyond the first university year, at which these conceptions cease to predominate the thinking of students, nor have they traced the level of knowledge and understanding which students need to acquire to dispell these conceptions. Linn (1986) states that reasoners appear to construct conceptions due to processing capacity limitations, availability of alternatives and lack of prerequisite knowledge. In this paper we show that students misconceive not just because of a lack of prerequisite knowledge but because of a lack of depth in knowledge as well. The latter limits the alternatives available to them when trying to understand and make sense of a situation.

In New Zealand high schools, students are gradationally exposed to various aspects of elementary mechanics throughout their lower forms (age group: 10-15yr) science. Physics instruction proper starts at form six (age group: 16yr). Mechanics is usually the first topic in each year of formal introductory physics learning in high schools and in the first university year. Hence it provides a rich domain for the study of students conceptions and knowledge base.

In this paper, classical mechanics (linear motion, circular motion, curved motion, oscillatory motion, motion along inclined planes, momentum and connected particles) is used to study the conceptions of form 6 students to second year undergraduates (age group: 16 to 20 years), to emphasize the level of knowledge and understanding required for students to correctly conceive the ideas involved for each situation, and to show that misconceptions cease to predominate as the students undergo more years of graduational physics learning and as they acquire the required knowledge. Answers to questions ranging from those requiring practically no prerequisite knowledge to those requiring depth of knowledge are discussed. Eight examples are used to study the conception level of students. We compare their knowledge base to the knowledge required to correctly perceive the situation. It is shown that students with sufficient depth of knowledge and understanding seem to have the right conceptions because they fully comprehend the situation.

4.2 Research Findings

Five sets of questionnires were administered to six groups of students (see table 4.1) subsequent to the commencement of the mechanics course for that year. Each questionnaire consisted of approximately ten short structured questions. The theme of the questionnaires was as follows: **Questionnaire 1**: Linear motion; **Questionnaire 2**: Circular motion; **Questionnaire 3**: Curved motion; **Questionnaire 4**: Oscillatory motion; and **Questionnaire 5**: Connected particles and motion along inclined planes. The scoring for the questionnaires was performed as follows: 2 for a correct answer; 1 if a semblance of knowing the answer was portrayed; and 0 if the answer was totally wrong.

The questionnaires were initially distributed to the form 6, the form 7 and the first year university undergraduates. Since even the first year students scored below 90% for each of the questionnaires, we also administered it to two groups of second year undergraduates (see table 4.1). The Major group had a A grade average at the first year while the Year 2 group had a C grade average at first year. The second year physics majors scored more than 90% in four of the five questionnaires. A group of first year undergraduates who had not studied any senior high school physics were included to show a difference in conception level in comparison to those studying physics.

The second year physics majors performed better than all the other groups in

Group	Description
Major	Second year undergraduates studying physics as a major
Year 2	Second year undergraduates studying a physics course
Year 1	First year undergraduates studying physics
Form 7	Form 7 students from three high schools in Christchurch. New Zealand
Form 6	Form 6 students from three high schools in Christchurch, New Zealand
No Physics	First year undergraduates (from a psychology class) without any senior high school physics background

Table 4.1: Student groups who participated in the study.

Questionnaire	Linear Motion	Circular Motion	Curved Motion	Oscillatory Motion	Inclined Plane
Major	100 96.4 6	96.7 83.4 6	96.7 88.4 6	94.0 76.1 6	84.5 74.5 6
Year 2	87.2 74.5 6	79.9 58.6 6	96.0 80.0 6	88.6 65.7 6	87.3 61.8 6
Year 1	83.0 74.6 25	87.7 61.4 15	88.8 72.5 16	87.6 70.1 16	81.8 71.5 15
Form 7	71.2 57.1 18	53.4 33.4 16	84.2 61.3 13	79.5 57.2 17	65.4 51.5 15
Form 6	68.6 57.2 27	32.8 16.0 27	69.4 45.7 30	59.2 36.3 25	55.1 40.9 30
No Physics	69.1 45.5 6	15.5 2.2 6	72.0 46.0 6	52.4 23.8 6	46.1 36.4 6

* Top row: Total mean percentage scores
* Middle row: Mean percentage scores for totally correct answers
* Bottom row: Number of students

Table 4.2: Mean percentage scores of groups by questionnaire.

questionnaires 1 to 4. The Year 1 group performed comparably to the Year 2 group. The form 7 students performed worse than the first year students but better than the form 6 students. The form 6 students in turn performed generally better than the first year students who had not studied physics at the university or in their senior high school years. The scores in table 4.2 show that the conceptions of the students are gradually corrected as they are exposed to more years of physics teaching and learning. Those with very little formal physics instruction (Form 6 and No Physics groups) have a greater number of misconceptions in comparison to the other groups. The second year physics majors did well in the first four questionnaires which dealt with the senior high school physics course. They faltered slightly in questionnaire 5 which dealt with the first year physics course namely, rigid bodies rolling down an inclined plane.

Table 4.2 shows that the scores of each group dropped substantially when only the exactly correct answers with explanation (scores of 2) were considered. There was a marked difference in the scores of the lower groups. This shows a lack of depth in knowledge. In numerous cases the students roughly knew the answers but could not substantiate it. This shows that the conceptions of students are linked to the incapability of providing a sufficiently elaborate explanation in support of their answers. Students with a higher level of knowledge and a higher level of physics instruction scored better, were able to provide explanations for their answers, and conceived better as well.

Groups	Questionnaire 1			Questionnaire 2				
	1a	1b	2	3	4i	4ii	4iii	4iv
Major	100	100	100	100	100	83.3	100	83.3
	100	100	83.3	83.3	100	83.3	100	83.3
Year 2	100	100	100	100	58.3	66.7	66.7	83.3
	58.3	100	75.0	66.7	66.7	66.7	41.7	83.3
Year 1	84.0	100	72.0	86.8	86.8	86.8	67.0	86.8
	76.0	100	48.0	40.6	60.4	86.8	47.2	86.8
Form 7	83.3	100	62.1	81.3	37.5	25.0	31.3	56.3
	50.0	100	16.7	12.5	37.5	25.0	31.3	56.3
Form 6	76.6	100	46.5	44.4	18.5	18.5	14.8	44.4
	40.7	94.5	16.5	3.7	11.1	11.1	7.4	44.4
No Physics	50.0	100	33.3	33.3	0.0	0.0	0.0	33.3
	25.0	100	0.0	0.0	0.0	0.0	0.0	33.3

* Top row: Total mean percentage scores
* Bottom row: Mean percentage scores for totally correct answers

Table 4.3: Mean percentage scores of groups for questions 1 to 4.

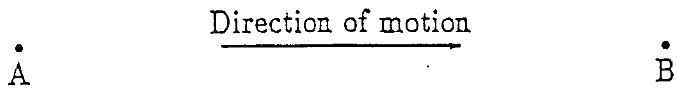

Figure 4.1: Initial position of cars.

For questions requiring the representation of forces, apart from the Major group all the other groups performed poorly. Students roughly knew the forces involved but did not have enough ancillary knowledge of these forces to correctly represent them. Examples of a poor understanding was portrayed by the representation of the gravitation force as g, the representation of ma as one of the forces acting on the object, and labelling forces by the actions producing it (see also studies by Erickson and Hobbs, 1978; and Gilbert et al, 1982). Some of the labels used are: pull force, push force, compressing force, spring force, gravity force, throwing force, motion force, etc. Due to this lack of understanding of the nature of forces they portrayed a lack of conception in answers to questions involving forces.

4.3 Conceptions and Knowledge

Some questions from each of the five questionnaires are discussed to highlight the conception and knowledge level of students. The knowledge required to answer each question is stated to show its relationship to the level of conception of the students.

4.3.1 Questionnaire 1: Linear Motion

Question 1 In figure 4.1, car X starts from rest at point B and uniformly accelerates. At the same time car Y is at point A moving with uniform speed. (a) Will car Y be able to overtake car X? (b) Is there a time when X and Y will have the same speed?

Knowledge Required: (a) The students have to fully understand the terms: displacement; velocity; and acceleration. To conclusively answer the question, students have to know how to combine these terms. (b) Only a knowledge of acceleration causing an increment in velocity is required.

The scores for 1(a) were markedly lesser than the scores for 1(b) for the Year 1, Form 7, Form 6 and No Physics groups (see table 4.3). For 1(b) students had the answers completely correct and were able to provide an explanation as well. For 1(a) the scores for obtaining the answers totally correct with explanation were much lower. Only students in the Major group were able to explicitly state the necessary condition by relating displacement, velocity and acceleration. The scores show that a greater exposure to physics makes a difference. For situations requiring basic information students have the correct conceptions. Where a combination of information is required, students misconceive because a higher knowledge of physics is needed.

Question 2 A ball is thrown vertically upwards. Draw and label the forces acting on the ball on its way up and down.

Knowledge Required: The existence of the gravitational force; its direction; and the definition of gravitational force for a constant mass (F=mg).

All the students in the Major and Year 2 groups knew the first two pieces of information. Only 1 out of 6 in each of these two groups did not know the information F=mg. For the Year 1, Form 7, Form 6 and No Physics groups: 24%, 28%, 36% and 50% respectively drew a force of propulsion acting on the ball on its way up as reported in studies by Hewson, 1981 and Jira et al, 1981; and 68%, 9%, 11% and 0% respectively knew that F=mg. The students with a poor knowledge of force representation labelled the gravitational force as g, gravity or gravity force. The scores show that a poor knowledge base causes poor conceptions. The Major and Year 2 students had a good grounding in the properties of the gravitational field and force representation. Due to this they had a good conception of the forces acting on the ball. None represented a force of propulsion for the motion of the ball. The Form 7, Form 6 and No Physics groups had a poor knowledge of the gravitational field and force representation leading to poor conceptions as well.

4.3.2 Questionnaire 2: Circular Motion

Question 3 Figure 4.2 represents a small body revolving in a horizontal circle, at the end of a string. The body swings around its path at a constant speed. Draw and label the forces acting on the body.

Knowledge Required: Students have to know and be able to represent the forces involved, namely: the tension in the string; and the gravitational force, mg. They have to know that the central force needed for the body to revolve in a horizontal circle is provided by the tension in the string.

This is the basic information required to understand the motion of the body. Without this information, the student would draw the forces without understanding

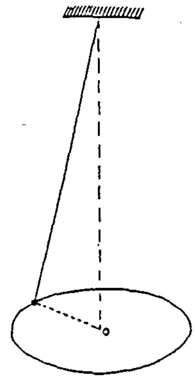

Figure 4.2: A body in motion in a horizontal circle.

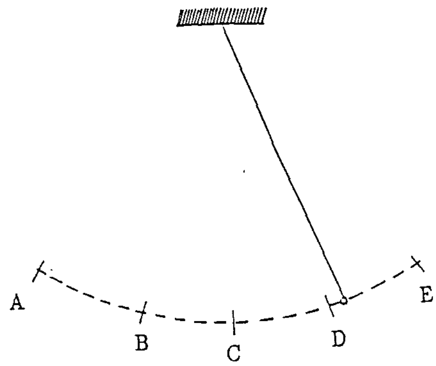

Figure 4.3: A body performing to and fro motion in a vertical plane.

and hence delineate wrongly.

The Major, Year 2 and Year 1 groups fared well (see table 4.3) as they had studied circular motion. In the Major group, 1 student represented the gravitational force as g. In the Year 2 and Year 1 groups 33.3% and 60% respectively labelled the forces wrongly even though they knew the forces involved. The Form 7, Form 6 and No Physics groups did not perform the task well (see table 4.3) as they did not have much knowledge of circular motion or force representation. They used the following labels for the forces acting on the system: centripetal; centrifugal; force for circular motion; and momentum force. None of the students in the Major and Year 2 groups drew a force along the path of the particle. In the Year 1, Form 7, Form 6 and No Physics groups 13%, 31%, 22% and 67% respectively drew a force along the path of the particle. They had the conception that *if a body is moving a force must be acting on it in the direction of motion* as reported in studies by Viennot (1979) and Watts and Zylbersztajn (1981). The Form 6 and No Physics students had a very low knowledge of circular motion (see table 4.3) and force representation and they portrayed a large amount of wrongly construed conceptions.

Question 4 Figure 4.3 shows a small body oscillating to and fro in a vertical plane between points A and E. Draw the path the body will take if the string is cut (i) in position B while the body is on its way to C; (ii) in position C while the body is on its way to D; (iii) in position D while the body is on its way to E; and (iv) when it arrives at E.

Group	Questionnaire 3		Questionnaire 4					Questionnaire 5	
	5	6	7a	7b	7c	7d	7e	8a	8b
Major	83.3	100	100	100	100	100	100	100	41.7
	83.3	100	100	100	100	100	100	100	33.3
Year 2	100	100	83.3	100	100	83.3	83.3	100	41.7
	100	100	83.3	100	100	83.3	83.3	100	16.7
Year 1	81.3	93.8	87.5	100	100	81.3	75.0	100	23.3
	81.3	81.3	87.5	100	100	81.3	75.0	100	13.3
Form 7	92.3	84.6	76.5	88.2	82.4	76.5	76.5	93.3	20.0
	92.3	69.2	76.5	88.2	82.4	76.5	76.5	93.3	13.3
Form 6	70.0	66.6	40.0	80.0	80.0	36.0	44.0	66.7	36.7
	63.3	43.3	40.0	80.0	80.0	36.0	44.0	66.7	6.3
No Physics	83.3	58.3	33.3	66.7	100	0.0	33.3	50.0	0.0
	83.3	41.7	33.3	66.7	100	0.0	33.3	50.0	0.0

* Top row: Total mean percentage scores
* Bottom row: Mean percentage scores for totally correct answers

Table 4.4: Mean percentage scores of groups for questions 5 to 8.

(For each of the questions a diagram was given, depicting the position of the body.)

Knowledge Required: Forces acting on the body (tension and gravitational force); the change in the velocity of the body; the repetitiveness and symmetricity of the motion; the velocity at A and E is zero; the velocity is tangential to the path of the particle; the velocity is a maximum at point C; and only the gravitational force acts on the body after the string is cut. For part (iii) a knowledge of the principle of conservation of energy is required to realise that the body will not reach higher than the level of E. To draw the path of the body an understanding of two dimensional curved motion is needed.

Students in the Major group performed well at this task as they had studied this topic and knew all the ancillary knowledge required to correctly conceive the paths of the body. The Year 2 students performed worse since they had not studied mechanics to a similarly higher level. They did not have such a good grasp of the ancillary knowledge unlike the Major group of students. The Year 1 students performed worse than the Year 2 students who had studied mechanics to a slightly higher level than them. The Form 7, Form 6 and No Physics groups performed poorly and had many ill conceived ideas of the paths of the object. The Form 7 group had studied projectile motion while the Form 6 and No Physics groups had not studied two dimensional motion. Their conceptions of the paths taken by the body were quite different and not generally in line with the theory of two dimensional motion (see also the study by Caramazza et al, 1981). The scores for question 4(iv) were higher than the rest (see table 4.3) because the answer fitted one of the paths which the students assumed the body would follow namely: falling vertically down irrespective of the position of the body when the string is cut. In contrast, the scores for question 4(iii) were much lower because many did not appreciate the energy considerations and drew the path of the body without relating the highest point of its path to the point E. Only students in the Major group took this finer detail into consideration.

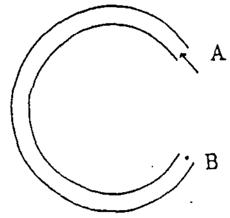

Figure 4.4: Configuration for question 5.

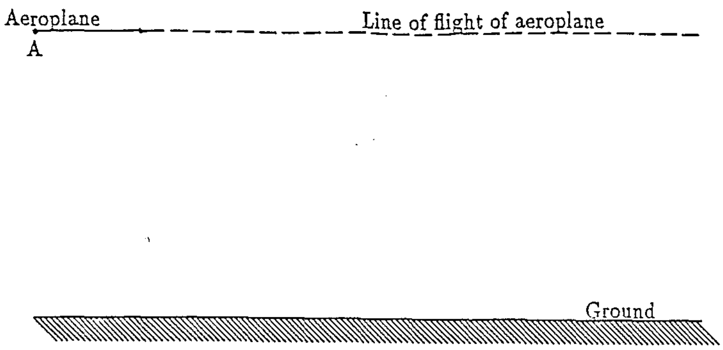

Figure 4.5: Path of Aeroplane.

4.3.3 Questionnaire 3: Curved Motion

Question 5 Figure 4.4 shows a hollow, circular tube fixed to a frictionless, horizontal table. You are looking down at the table. A ball is shot into the end A of the tube to leave at the other end B at high speed. (The question is taken from Halhoun and Hestenes, 1985)

Knowledge Required: The particle needs to be constrained to move in a circle; and it has a tangential velocity while in circular motion.

The information required to answer this question is quite elementary. All the groups performed quite well. Many were able to provide explanations in support of their answers (see table 4.4). In the Major group, one person drew the path of the particle as a curve. Upon further questioning she realised her mistake. She was under the impression that the particle was constrained to move in a circle even upon leaving the tube. In the Form 6 group, the students knew that the particle moves off in a tangential direction due to the tangential velocity it has while performing circular motion and only 6% drew the path of the particle as a curve. Thirteen percent drew straight, non tangential paths. Even the No Physics group performed well at this task since the information required was elementary and within their grasp. None in this group drew the path of the particle as a curve. Very few students had wrongly concieved ideas of the path of the particle unlike the findings reported by McCloskey et al (1980) and Halhoun and Hestenes (1985) where many students had misconceptions on the path of the particle.

Question 6 The aeroplane releases a bomb at point A (see figure 4.5). Draw the path taken by the bomb in falling to the ground. Mark four positions of the

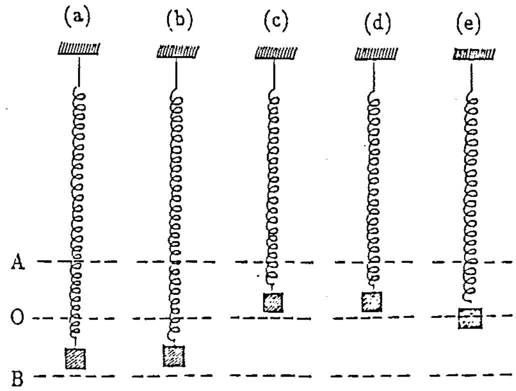

Figure 4.6: An object in vertical motion at the end of a spring.

bomb along the path you have drawn. For each of these, indicate the corresponding position of the aeroplane.

Knowledge Required: The bomb has the velocity of the plane; upon release the bomb acquires vertical motion due to gravity; the horizontal motion of the bomb is unaffected by gravity; the horizontal and vertical motions combine to give the path of motion of the bomb.

The Major, Year 2 and Year 1 groups had this information (see table 4.4). They knew the path the bomb would take in falling to the ground and were able to accurately relate the position of the bomb with respect to the plane. The Form 7 students knew that the bomb would follow a curved path (projectile motion) but were not totally aware that the horizontal motion of the bomb would be identical to that of the aeroplane. The Form 6 and No Physics students were unaware of the theory involved and had many ill concieved ideas of the motion of the bomb and its relation to the motion of the aeroplane. Even then quite a few (see table 4.4) drew the path of the bomb correctly but were unable to provide an explanation in support of their answers. They were unable to relate the motion of the aeroplane to that of the bomb.

4.3.4 Questionnaire 4: Oscillatory Motion

Question: 7 An object hanging from a spring is set into up and down motion between A and B. O is the centre of oscillation. Mark the direction of the acceleration of the body when it is in the position shown in figure 4.6 and is moving (a) down; (b)up; (c) down; (d) up; and (e) through position O on its way up or down.

Knowledge Required: The acceleration is always towards the centre of oscillation; and it is proportional to the displacement of the object from the centre of oscillation.

The students in the Major group did equally well in all the parts of the question. They had a sound grounding in the theory of linear simple harmonic motion. All the other groups did better for questions 7(b) and 7(c) in comparison to questions 7(a) and 7(d) (see table 4.4).

For questions 7(b) and 7(c) the students would have obtained the correct answer by intuitively assuming the acceleration in the direction of motion of the object. For questions 7(a) and 7(d), they had to know that the acceleration acts towards the centre of oscillation to obtain the correct answer. The Form 6 and No Physics students performed poorly in questions 7(a) and 7(d) as they had no knowledge that in simple harmonic motion the acceleration always acts towards the centre of oscillation. The higher scores for 7(b) and 7(c) indicate that students without the prerequisite knowledge generally assume the acceleration to be in the direction of motion.

For question 7(e), students did not perform so well as they were not aware that the acceleration at the centre would be zero since it is proportional to the displacement from the centre. The conceptions of students in the Major group were correct as they had a very sound grounding in the theory of oscillatory motion. For the Year 2 and Year 1 groups 1 of 6 and 3 of 16 students respectively had the wrong conception of the motion of the object. The students in these groups had studied oscillatory motion but had not delved into it in the same depth as the students in the Major group. They had studied it to a greater depth in comparison to the Form 7 group. Consequently their conceptions were better than those in the Form 7 group.

4.3.5 Questionnaire 5: Connected particles and motion along inclined planes

Question 8 A disc and a solid cylinder of equal mass are timed in their motion down an inclined plane over the same distance. Which will reach the base of the plane in a shorter time if the plane is (a) frictionless, so that neither object rolls? (b) rough, so both the disc and the cylinder roll down the plane?

Knowledge Required: (a) A constant acceleration acts on both the objects; they may be treated as particles. (b) The moment of inertia of the objects is equal; the rotational kinetic energy is $1/2I\omega^2$; the translational kinetic energy is $1/2mv^2$; and the conservation of energy principle.

Except for the Form 6 and No Physics groups, the rest scored well in question 8(a) (see table 4.4) as they had a good grounding in straight line motion with constant acceleration. In the Form 6 and No Physics groups 33.3% and 50.0% respectively had the conception that the objects would reach the base at different times. In the other groups practically none of the students had this false conception.

In contrast to question 8(a), the scores for question 8(b) (see table 4.4) were rather low. The scores for question 8(b) show that many students thought the objects would take different times to reach the base of the inclined plane. Those who correctly stated that the objects would reach the base at the same time were unable to provide an explanation in support of their answers. Motion of rigid bodies is a topic which is studied in detail in the first university year. The Year 1, Form 7, Form 6 and No Physics groups did not have much knowledge of the information required. At the time of administration of the questionnaire the topic had not been studied by the first year students. Even the Major and Year 2 students who were supposed to have knowledge of the motion of rigid bodies portrayed poor conceptions for this question. Apart from the knowledge of the motion of rigid bodies, this question requires the application of the energy principle. The dynamical force method may also be used but it involves tedious mathematical manipulation.

This was the only question that required a thorough knowledge of first year university coursework and students in the Major group had poor conceptions of it. More stated that the cylinder being a larger object, although of the same mass, would have a larger moment of inertia (rotational inertia) and hence, would take longer. In fact the dimensions of the object cancel as for the sliding case. This wrong conception arose due to a lack of the ancillary knowledge that the distribution of mass of the object about the axis of rotation needs to be considered.

The examples discussed show that students have correct conceptions where the knowledge required is elementary. The misconceptions increase as the amount of knowledge required to conceive the situation increases or when a combination of the elementary knowledge is required. Even groups (Form 6 and No Physics) who had a low knowledge base did not perform too badly in tasks requiring little ancillary knowledge. This indicates to us that students do not really misconceive much. They just have a bad understanding of the situation due to a lack of ancillary knowledge or just do not have a knowledge of the information required. In situations where the students had the required knowledge the misconceptions portrayed were minimal. However, a small percentage of misconceptions are usually portrayed in all such cases. This may be likened to students not scoring full marks in the examinations even though they may have studied for it at length.

Physics is a subject which requires the maturity of ideas in the minds of the students. This was highlighted in the discussion for the answers to question 8(b). The Major group students fared poorly in this question as they had only studied the topic the year before. Students seem to correctly conceptualise situations requiring elementary knowledge only when they have progressed to a substantially higher order of knowledge in that domain. They did well in all the other questions because they had obtained graduated repetitive exposure of 2 to 3 years for the the knowledge required to answer the questions. On the other hand, the Form 7, Form 6 and No Physics students had difficulty with most of the ideas because they had not been exposed much to these ideas. These groups also had more misconstrued conceptions as well. The number of correct conceptions increased with the physics knowledge of the students.

4.4 Conclusion

In this paper the knowledge base of the various groups has been determined for five sections in mechanics, namely linear motion, circular motion, curved motion, oscillatory motion, connected particles and motion along inclined planes. It was obvious that more years of physics learning provided a broader and deeper knowledge base, as should be the case. Examples from these sections have been discussed to show that students with a poorer knowledge base have poorer conceptions, misconceptions arise due to a lack of knowledge required to fully comprehend the situation, students have good conceptions in topics which they have repetitively studied in gradually increasing depth over a few years.

The paper has shown that misconceptions are strongly portrayed only in instances where the knowledge required to comprehend the situation is lacking. Our previous studies on knowledge structure and conceptions for reflection and refraction (Singh and Butler, 1989a,b,c) have shown that wrong conceptions can be portrayed because of a lack of the necessary ancillary knowledge or because of a lack of appropriate organisation of this knowledge into a conceptual framework.

When the students do not have enough ancillary knowledge and sufficient understanding to apply the principles of physics to a given situation they will be unable to answer correctly. They will then answer the question wrongly and portray a lack of perception of the situation. This answer should not be considered a wrong preconception but merely a wrong answer or even a limited conception. Only if the students have the knowledge and understanding but still produce the wrong idea then may we term it as a misconception. Distinction needs to be made between a merely wrong answer and a wrong preconception. To do this the knowledge and understanding of the students needs to be compared to the knowledge required to correctly conceive the situation.

Chapter 5

Measuring Students' Knowledge by Card Sorting of Physics Words, Phrases and Equations

5.1 Introduction

The purpose of research in science education is to obtain insights that will lead to a better understanding of science by students. The themes of much research in science education have been to determine the preconceptions and misconceptions in the minds of students (see review article by Driver and Erickson, 1983), to study the way experts and novices think and process the subject matter (Chi et al, 1981) and to find ways and means of most effectively changing the students perceptions and knowledge structure towards those of experts (Osborne et al, 1985). Osborne through the *Learning in Science Project* had a major influence on the teaching of school science in New Zealand. Most New Zealand secondary science teachers are conscious of the need to understand the thinking of students and have been influenced to modify their teaching style (Munroe, 1989).

We have studied the conceptions and knowledge structures of students for optics (Singh and Butler, 1989a,b,c) and mechanics (Singh and Butler, 1989d). We used questionnaires and interview methods to determine the conceptions of students and from the answers provided their knowledge structures were deduced. The most significant conclusion from these studies was that in their minds high school students and first year university students showed they do not have connections between concepts and within topics in physics. Students learnt by content and not by using conceptual connections. Perturbed by these lack of connections we adapted the free card sorting methods used by psychologists to study the cognitive structures in people's minds.

This paper attempts to measure the knowledge structures of 8 first year students and 10 experts (8 graduate students and 2 lecturers). The first year students cannot be considered novices since they had completed 2 years of senior high school physics. Furthermore, few words, equations and principles were not recognised by them. At each of seven sessions the subject was given one of seven sets of cards and allowed to group the cards as they wished without any constraints. Four of the sets were used to study word associations and groupings within different environments. Two sets were of equations and one set on principles and laws. These sorting exercises may be easily replicated in the classroom for usage by the teacher to determine word associations and knowledge structures of students.

For each of the free card sorts, subjects were asked to group the cards together in any order. No time constraint was applied. Subjects were given blank cards so that they could make copies of cards for inclusion in any number of groups. Upon completion of the sorting they were asked whether there was any order within the groups and to draw a structure of connections between the groups formed. This enabled the knowledge structures of each subject to be studied in seven different ways. Each sort set provided a different environment for sorting the cards and tracing the knowledge structures.

In physics, a word can represent a topic, a concept, a physical quantity or simply a connective or descriptive quantity. Knowledge structure is the information processing term for organised networks of information stored in semantic memory (Champagne et al, 1981). Shavelson (1974) states that *a critical problem for instructional research is to examine behavioural outcomes of learning structure in order to provide information for answering questions such as: to what extent does the structure in a student's memory correspond to the subject-matter structure? and to what extent structural learning leads to a better understanding of the subject?* Johnson (1964) used words to study interrelated associations among physics concepts. The role of knowledge structures for learning subject matter in geometry has been researched by Greeno (1978), and Chi et al (1981) used sorting of problems to investigate how experts and novices represent physics problems in relation to their organisation of physics knowledge.

A general cognitive structure encompassing the features portrayed in the individual knowledge structures of the subjects is propounded. The knowledge structures of first year students is compared to those of the experts. Similarities are drawn between the knowledge structure of the subjects and the structure of physics as presented in texts used in first year university courses (Halliday and Resnick, 1988; Ohanian, 1988; and Sears et al, 1987). It is shown that the structure in the minds of the subjects is a combination of main physics topic areas, main categories, subcategories, and physical constructs mentioned in the texts and used for teaching the subject. Even university graduates and lecturers did not duplicate many cards to relate key words from one topic area to another. They were aware of the connections but did not portray them in the groupings or connections between groups.

The sorting of equations requires a depth of knowledge; the recognition, understanding and discrimination of symbols used; and the associated ancillary knowledge

Sort Labels	Cards Description	No. of Cards
Common	Words commonly occuring in the various physics sections	40
Mechanics	Words from the mechanics section	57
Physics	Words from various physics sections	56
Real	Words from various physics sections and having non physics meaning as well	47
Equations	Equations from various physics sections	71
Mecheq	Equations from the mechanics section	59
Principles	Names of principles and laws from various physics sections	46

Table 5.1: Description of the sort groups.

needed for application of the equations. For sorting the principles and laws, a knowledge of the names and the associated ancillary knowledge is required. Word sorting exercises can require merely a superficial knowledge for making simple associations, or can require a concrete understanding for making lateral and longitudinal connections within and between groups of words. Free word sorting provides a flexible tool for studying different aspects of the knowledge and understanding of students.

The two equation sets, and the laws and principles sets were used to check and confirm the similarity of structures obtained through the word sorting exercises. The four word sets were used to determine associations between pairs of words, the classification of words applicable to more than one main physics topic area, the classification of words with a single main physics topic area and the various classifications of the same words in the different environments provided by the four word sorts. The word sorts were used also to study whether simple conceptual relationships (e.g. F=ma) are used by the subjects for associating and sorting the words. Johnson (1964) found that students did not associate words using these basic relationships.

The knowledge structures propounded, and the common associations of words and equations found, are highlighted here for possible use in teaching the lateral and the longitudinal connections within the structure of physics. These implications for teaching are discussed with a view to using free card sorting exercises in the classroom to improve the understanding of students and to modify the knowledge structure of students. It is integral to the teaching process that the teacher knows the meanings that students take from various words and the ways in which they associate words with one another and with the various topics in physics.

5.2 Methodology

The material for the seven sort sets was selected from three standard first year physics texts (Halliday and Resnick, 1988; Ohanian, 1988; and Sears et al, 1987) The description of and a one word label for, the card sets is given in table 1. The words, equations and principles were printed on 9cm by 5cm cards. Some similar words were included between the word sets to determine the effect of different environments provided by the various card combinations within each sort.

5.2.1 Subjects

Nineteen subjects from the physics department at the University of Canterbury, participated in the study . They comprised 2 senior staff who had lectured first year and higher level physics for upwards of 25 years, 6 Ph.D. students, 2 other graduate students and 9 first year students studying the advancing physics course. The 9 first year students were chosen using their physics university qualifying results such that they were evenly distributed to include students with above average, average and below average grades. One first year student with below average grades dropped out halfway through the study. All the subjects volunteered for the study.

5.2.2 Data Gathering

The 7 card sorting exercises were administered individually to the subjects over a period of 11 weeks. Each subject sorted at most once per week. The sortings were administered to each subject in a different order. For each sort the subjects were given the following instructions prior to task commencement:

> You may take as long as you wish in sorting the cards into groups. Blank cards are provided so that you may make copies of the cards for inclusion in more than one group. Form as many groups as you feel fit. Any cards that do not fit into the groups formed may be placed aside. Cards that you do not recognise do not have to be sorted. Label each group after you have completed sorting the cards.

Upon completion of the sorting, the time was recorded. The subjects were asked whether there was any order or subgrouping within the groups. Where items did not match the group labels in an obvious manner we queried the reasons for the classification. Finally the subjects were asked to draw a structure of connections between the groups they had formed. They were reminded not to force connections but to draw them only as they existed in their minds so as to show how they remembered or learnt the material. The time of completion of the task was recorded.

5.3 Research Findings

There was no substantial difference in the sorting styles of the various subjects. Some placed the cards in a rough mess in front of them to obtain an overview and then started picking cards to form groups. Others formed groups as they came across the cards. If a card did not fit an existing group they either formed a group with it or placed it aside for later consideration. Some wrote cards for inclusion in more than one group while sorting and others did this upon completion of the sorting.

The 2 lecturers arranged the groups in a certain order while sorting. The graduate students were able to create order in their groupings after sorting and were able to label the groups quite easily. They were able to make connections between groups if they thought it existed. The first year students formed groups in a haphazard manner and those with average and below average grades had difficulty in assigning labels to the groups or deciding whether there were connections between groups.

There was little difference in the number of groups and subgroups formed by the first year students and the others. The first year students usually formed about 1 group less than the others. All the subjects formed the most groups for the 2 sets of equation sorts followed by the principles sort and the least for the 4 sets of word sorts. The number of cards had no significant effect on the number of groups formed.

The longest time taken to complete the sorting session was 91 minutes and the shortest time was 26 minutes. The subjects took generally longer to sort the equations in comparison to the other sorts. The number of cards that the first year students did not recognise were on the average higher than for the graduate students, while the lecturers recognised all.

5.3.1 Cards Duplicated

Each person on the average duplicated only 4 cards per sort. Two of the graduate students duplicated a maximum of 14 and 11 cards per sort respectively. The graduate who once duplicated 14 cards formed 7 non-connected groups for that sort. The maximum number of cards duplicated by a first year student was 5. The words energy and magnitude in the Real group of words were repeated a total of 16 and 9 times respectively. Apart from this no single word, equation or principle was repeated more than a total of 5. The experts either created groups for the more general terms or made connections between them and other groups when drawing the between group connections. The first year students generally assumed a single meaning for each card. They did not make many connections between the groups. They grouped cards in groups within which they first encountered the words and equations. with a topic recently completed or within a topic in which the word or equation was most encountered.

5.3.2 Cards Signifying a Specific Meaning

There were certain words that were placed in the same groups by all the 18 subjects. Examples are image, pitch and temperature which were in both the Real and the Common sets. Further, most subjects labelled these words groups as Optics or Light, Sound or Waves and Heat or Thermodynamics respectively. The words solenoid, lens, dielectric and current in the Physics group were placed in roughly the same broad groupings by all the subjects. The cards moment of inertia, torque, tension and rigid in the Mechanics sets were sorted into similar mechanics groupings by

Word	No. of groups created	Groups with which word is most associated 1	2	3	4
Acceleration	7 (58)	kinematics (21)	motion (17)	vectors (6)	forces (6)
Action	7 (57)	forces (20)	Newton's law (13)	mechanics (11)	waves (4)
Density	8 (60)	thermody. (14)	fundamentals (11)	matter prop. (11)	mechanics (7)
Force	8 (57)	mech. forces (26)	motion (17)	Newton's law (6)	electricity (2)
Oscillation	9 (65)	waves (24)	SHM (17)	osc. motion (11)	pendulum (4)
Phase	7 (67)	waves (26)	SHM (9)	osc. motion (8)	thermody. (8)
Polarisation	3 (56)	optics (31)	waves (22)	electricity (3)	—
Pressure	6 (60)	thermody. (21)	matter prop. (14)	forces (11)	fluids (6)
Reaction	6 (62)	matter prop. (15)	forces (15)	Newton's law (13)	chemical (10)
Resistance	5 (61)	electrical (37)	mechanics (12)	electromag. (6)	solid state (4)
Resonance	5 (57)	waves (30)	oscillations (10)	SHM (8)	sound (6)
Wave	4 (63)	waves (44)	sound (11)	SHM (5)	oscillations (3)

*Parenthesis indicates number of times word was mentioned in the categories.

Table 5.2: Groups created for general words.

practically all the subjects as well. Equation cards were more commonly placed in similar groups due to the combination of information inherent within each equation.

5.3.3 Cards with General Meanings

Table 2 shows the groups into which cards with a general meaning and applicable in various physics topics were sorted. For each word the 4 groups to which it is most associated are given. Most of these words were sorted into groupings related to the origin or context first encountered in physics learning. The experts tended to group words according to the first occurrence in a standard text. Pressure is an example of one exception. It is first used in mechanics but it was grouped more within thermodynamics and a duplicate card was not made by any of the subjects. Resonance and resistance were other such words grouped by the topic within which they are most utilised.

5.3.4 Widely Applicable Words

Examples of widely applicable words used in the study are given in table 3. These words seem to hold a specific meaning for the first year students. Even the graduate students on the average duplicated these words a maximum of only twice. Yet these words typify the lateral connections within the structure of physics.

The word **Critical** within the Common and Real goups is a good example of a word with various meanings. It is used in the standard texts in various contexts,

*Sets	Word	Group Descriptors
2	Critical	optics(9); chemical reactions(11); nuclear(3); thermodynamics(15); simple harmonic motion(2); superconductivity(2); elasticity(7)
2	Equilibrium	simple harmonic motion(8); stability of equilibrium(6); reactions(9); equilibium of states(15); nuclear(1)
1	Induction	electromagnetic(12); electrostatics(5); mathematics(1)
2	Intensity	light(18); fields(2); electromagnetic(3); thermodynamics(4); waves(7); sound(3)
1	Parallel	circuits(10); light(6); mathematics(5)
1	Series	circuits(15); mechanics(1); mathematics(2); waves(3)
1	Flux	magnetic(3); electric(6); light(3); thermodynamics(5); waves(2); electromagnetism(4)
1	Energy	mechanics(5); energy(10); work(2); thermodynamics(7); electric(6); electromagnetic(2); chemical(1)
1	Field	gravity(1); electric(10); magnetic(2); superconductivity(1); electromagnetic(3); mathematics(2); field(3)
1	Gradient	electric(3); gravity(3); temperature(1); mathematics(14)
1	Magnitude	electric(1); mathematics(7); waves(6); superconductivity(1); mechanics(4); thermodynamics(1); light(2)
1	Medium	waves(7); electricity(2); optics(7); propeties of matter(5)
1	Normal	mechanics(4); light(6); vectors(2); mathematics(8)
1	Power	energy(10); light(3); mechanics(5); electricity(6)
1	State	matter(4); equilibrium(2); thermodynamics(8); chemical(4)

* Number of sorting sets within which word was included.

Parenthesis indicates number of times word was grouped using the group descriptor.

Table 5.3: Grouping of words widely applicable in many main physics topic areas

namely: critical angle (total internal reflection); critical damping (simple harmonic motion); critical damping (ac circuits); critical temperature, point, volume, pressure and density (thermodynamics); critical transition temperature (superconductivity); critical point (deformation); critical reactions (chemical); and critical mass (nuclear). Table 3 shows that it was mentioned for 7 of these 9 contexts. Out of 2 sort sets it was mentioned 49 times by the 18 subjects. This gives a repetition on average of 1.4 times by each candidate when it could have been a member of 9 main groups. This shows a lack of lateral thinking. The 2 lecturers connected these words to the most number of groups yet even they covered fewer than 50% of the possibilities. This clearly does not signify lack of knowledge rather it hints that to each subject each word cues a single concept.

5.3.5 Pairs of Words

Pairs of words which may be closely associated were included within the 4 sets of word sorts. Table 4 gives the responses of the subjects to 11 such pairs of words, and shows that some *obvious* pairs are created while others are not.

Action and *Reaction* were in the Common, Mechanics and Real sets. Table 4 shows that nearly all the first year students grouped these words together each time, but the experts did not except in the Mechanics set. This suggests that the environment of the cards does affect the groupings.

Word pair	Sort set	Year 1		Experts	
		Tog.	Sep.	Tog.	Sep.
Action-Reaction	Common	6	2	6	4
	Mechanics	8	0	9	1
	Real	6	2	6	4
Time-Period	Common	2	6	3	7
	Mechanics	2	6	1	9
Elastic-Inelastic	Mechanics	8	0	8	2
Projectile-Time of flight	Mechanics	8	0	10	0
Work-Energy	Real	6	2	9	1
Strain-Stress	Real	8	0	10	0
	Mechanics	8	0	10	0
Reflection-Refraction	Physics	8	0	10	0
Conduction-Convection	Physics	4	4	6	4
Parallel-Series	Common	5	3	7	3
Phase-State	Real	2	6	3	7
Tangential-Normal	Real	3	5	9	1

*Sep.: number of subjects grouping the pair separately.

*Tog.: number of subjects grouping the pair together.

*Experts: the lecturers and the graduates.

Table 5.4: Associations of pairs of words.

Projectile and *Time of Flight* within the Mechanics set were sorted together by all the subjects, even though *Time of Flight* has a more general application. The texts also only use it in this narrow context.

In contrast *conduction* and *convection* were grouped together only 50% of the time. Convection was grouped within thermodynamics. Only the 2 lecturers, 2 of the graduate students and 2 of the first year students with above average scores classified conduction within thermodynamics as well as electricity.

5.3.6 Conceptual Relationships

Table 5 shows 7 examples of basic equations in physics which may be formed by conceptually combining the word cards into similar groups. It is obvious that the subjects do not sort conceptually to form relationships. This is in agreement with the findings of Johnson (1964) who used word association tasks to show that subjects do not associate words through conceptual relationships.

Ohm's law was a rare case whereby the components of V=IR were grouped within the same group by all except 2 of the subjects. The grouping presumably simply arises because they are three key components within electricity.

Usually even basic conceptual relationships like *period = 1/frequency*, *displacement = velocity* x *time* and *force = mass* x *acceleration* were not formed from the word groups created.

Conceptual Relationships	Sort set	Year 1		Experts	
		Concept.	Disjoint.	Concept.	Disjoint.
T=1/f	Common	3	5	2	8
	Mechanics	1	7	2	8
F=ma	Mechanics	1	7	1	9
	Physics	4	4	9	1
a=v/t	Mechanics	3	5	5	5
s=vt	Mechanics	4	4	4	6
p=mv	Mechanics	1	7	4	6
V=IR	Physics	7	1	9	1
W=Fs	Mechanics	1	7	2	8

*Concept.: number grouping conceptually.

*Disjoint.: number not grouping conceptually.

Table 5.5: Associations in word sorts exhibiting conceptual relationships.

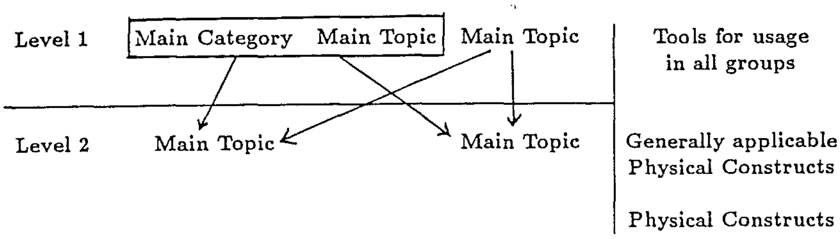

Figure 5.1: Structure of a lecturer.

5.4 Knowledge Structure

The structures used by the 18 subjects in categorising the word sorts, the equation sorts and the principles sort were similar. The structures were developed using main physics topic labels used in physics texts (e.g. mechanics, waves, thermodynamics, electricity, etc.), main categories within each main topic (e.g. in mechanics: kinematics, simple harmonic motion, dynamics, rotational motion, etc.), subcategories within each main category (e.g. in kinematics: motion in a straight line, free fall, motion along an incline, motion in a plane, etc.) and physical constructs within each subcategory (e.g. springs, pendulums, engines, friction, collisions, gravity, oscillations. etc.).

The experts and the above average first year students used mainly main topics, main categories and subcategories. The first year students with average and below average grades used physical constructs more often. The lecturers and some of the graduates grouped generally applicable terms into separate groups and treated them as conceptual constructs. The lecturers used these conceptual groupings as tools feeding into the rest of the structure. Figure 1 gives a structure drawn by one of the lecturers.

When comparing the Mechanics and Mecheq sorts with the broader sets Real, Common, Physics. Equations, and Principles sorts it was obvious that the experts went from using subcategories to using main topics (i.e. a change from specifics to

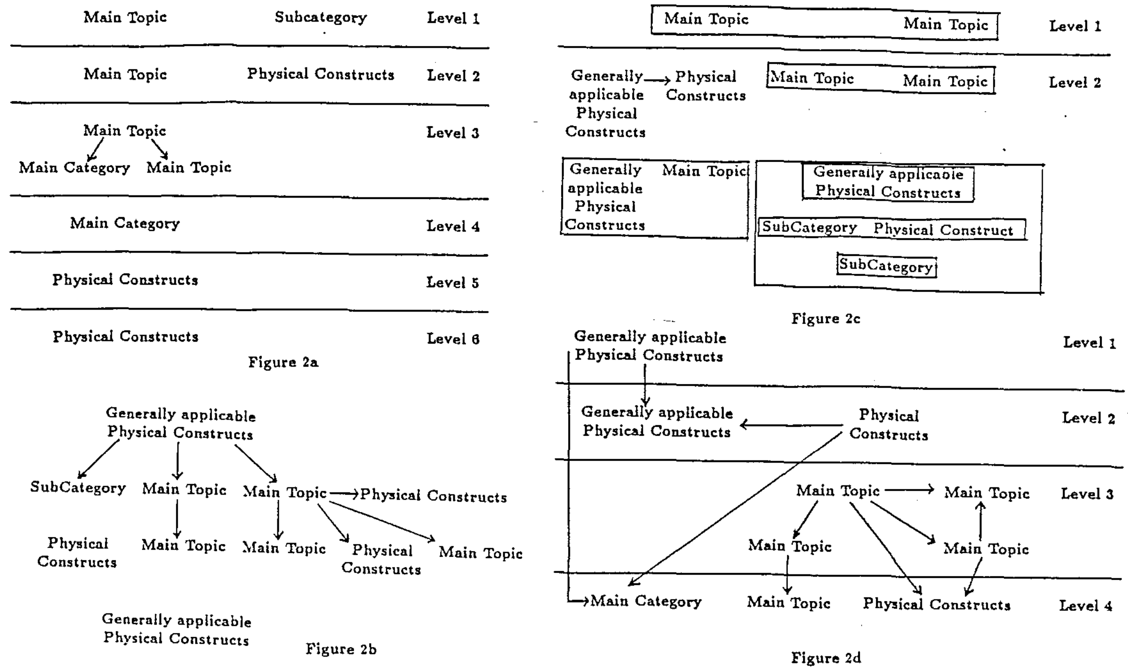

Figure 5.2: Structures developed by first year students.

generalities), while the first year students went from using main categories to using physical constructs (i.e. a change towards situation specifics).

For the 7 sorts, each first year student and 2 graduate students used a single specific style for their 7 structures, while the other 8 experts used a repertoire of combinations to delineate their 7 structures. The 2 lecturers classified and ordered the main topics as they would teach them, closely resembling the structure in textbooks and were conscious of this. The graduates and first year students had no such order between main topics or main categories. Heirarchical thinking featured in the structures of the lecturers and graduates when connecting the main topics and main categories and within the main categories and the subgroups for the first year students.

Four of the 56 structures drawn by the first year students are given in figure 2. Figures 2a to 2c give the structures of the average and below average students while figure 2d gives that of an above average student. The levels indicate order in which the material is taught or learnt from basic to complex material or just a conglomeration of slightly related subgroups. Material that is needed as a prerequisite to understand later subject matter is classified in the upper levels. Unlike the structure of the lecturers (see figure 1), those of the average and below average students do not have many connections. Their structures are a conglomeration of independently existing groups. The essential difference between the first year students and the experts lies in the connective structure and the finer ordering and subdivision of groups. The lecturers had the most connective and flowing structure. The first year students with above average grades had connective structures (see figure 2d) essentially similar to those of the graduates.

5.5 Implications for Teaching

It has been shown that certain words hold a specific meaning while others have multi-faceted meanings. Physics is a study of connections. The *better* laws, like F=ma, are better because they have boader applicability. One of the aims of teaching physics must be to build a knowledge of the structural connections between phenomena. Words with multi-faceted meanings ought to be used to make the lateral connections between concepts, main topics and main categories in physics. Figures 1 and 2 show that few lateral connections were delineated in the structures of the subjects. Table 3 shows that (except for the lecturers) the generally applicable terms were classified into very few groups.

Equation sorting can be used to help students to sort out the various meanings that a symbol may hold when used in different main categories. The Cambridge examination syndicate (United Kingdom) has adopted and advocates the usage of certain standard symbols (Cambridge syllabus guide, 1988). Although there is no international agreement of symbol usage examination boards in the United Kingdom and certain countries affiliated to these boards use these *standard* symbols in the teaching of Physics. Symbols can also be used to connect and distinguish between the various combinations of physical constructs within each equation. The equation sorting can be used to relate the connections between the physical constructs within an equation or between equations.

Card sorting exercises can be easily performed in the classroom. Students' understanding and knowledge of connections between and within topics, words and equations can be determined and clarified through these sorting exercises. The many structures developed by the students can be discussed to show the various possibilities of flow and connection within the structure of physics. Sorting can be used to determine the basic knowledge required to form structures. Sorting words, equations and principles require varying amounts of knowledge. For the word sorts, making longitudinal and lateral connections requires knowledge of the various facets and usage of the words. For sorting equations, the discrimination and meaning of the symbols, the recognition of the equation and the ancillary knowledge which goes with each equation all needs to be consciously realised.

Studies on knowledge structures of students for reflection and refraction (Singh and Butler, 1989b,c) have shown that students learn and commit content to memory through a conglomeration of independently existing groups. Sorting exercises can be used to teach various aspects such as associative connections, longitudinal order, clustering of similarly applicable constructs, lateral connections, symbol recognition and discrimination, and simple to complex subject matter arrangement. Students could be made aware that although order and structure within physics must be learnt, there is no single correct way of depicting its structure. Learning to think in terms of connections and flow between topics and concepts may be enhanced through such card sorting exercises. Furthermore, it will encourage students to think in terms of connecting and associating the various main topics, main categories, subcatgories and physical constructs in physics.

5.6 Conclusion

In this paper we have reported on the use of free card sortings of words, equations and principles to determine how novice and expert physicists classify words and equations. It has been shown that words are grouped together through their occurrences within a topic and their applications within the various main topic areas of physics. They are not grouped using conceptual relationships. Words with multi-faceted meanings were generally placed within groups within which they were first encountered or in groups within which they are most utilised.

The knowledge structure of experts (lecturers and graduates) and relative novices (first year students) has been studied through their grouping and organisation of words, equations, and principles and laws. The lecturers created structures that were most finely divided and with the most connections while the first year students had the least connections and subdivision. The lecturers made lateral connections by categorising generally applicable terms separately into groups. They then connected these groups to all the other groups. The structures of the other 16 subjects lacked this richness of lateral connections. The research has shown that graduate students and university lecturers did not form many duplicates to relate key words from one area in physics to another. They can certainly make these connections when asked but our sample definitely did not volunteer them or portray them much in their card sortings.

The 7 sorting exercises showed that irrespective of whether words, equations or principles were being sorted, the subjects created structures comprising a combination of main physics topics, main categories within the main physics topics, subcategories within the main categories and physical constructs within the subcategories. The structures delineated by the subjects were essentially similar to those used in physics texts.

The implications of card sorting exercises for teaching have been discussed as card sorting is a simple classroom exercise. The various structures the students create may be compared and discussed by teachers to modify the knowledge structures of students. Association between words have been discussed to show that these may be used to teach connections between topics in physics or to structure a particular topic. The various learning aspects of card sorting exercises have been mentioned for teaching and enhancing the continuity of thought within physics.

Chapter 6

Conclusion

There is general applicability of knowledge structure within the learning process. It has been shown that for optics, the conceptual knowledge level of first year undergraduates is essentially at the same level as that of the high school students. The conceptions of students have been traced to a lack of ancillary knowledge, a surface understanding of the subject matter learnt, content teaching and learning, and style used both in the student textbooks and in the texts consulted by the teachers. Many of the conceptions of the students arise because of a lack of depth in knowledge and organisation of the subject matter learnt.

To affect the conceptions of students, their prior knowledge has to be taken into account. For both reflection and refraction a conceptual knowledge structure encompassing all the content catgories used by students has been proposed. These may be used to show the organisation of the content and to help in modifying the knowledge structure of students. For reflection a modified conceptual teaching approach has been recommended.

In mechanics the conceptions of students have been studied and it has been shown that misconceptions are strongly portrayed only in instances where the knowledge required to comprehend the situation is lacking. Students portray a lack of perception of the situation when they do not have enough ancillary knowledge and sufficient understanding to apply the principles of physics to a given situation. Where the necessary knowledge required to perceive the situation was present the students were able to conceive the situation correctly.

Through the free card sorting exercises, it has been found that words are associated together through occurence within a topic and their main application within the various mainstreams of physics. They are not classified or associated through conceptual relationships. Words with multi-faceted meanings are generally placed within groups of their basic origin or in groups within which they are most utilised.

The study of knowledge structures has shown that the lecturers have finely divided and connected structures followed by the graduate students with the year 1 undergraduates having the least connections and subdivisions. Except for the 2 lecturers lateral connections were generally missing from the structures of the subjects.

The structures formed comprised a combination of mainstream physics labels, main categories, subcategories and physical constructs. The structures delineated by the subjects were essentialy similar to those used in physics texts. The structures of the subjects have been used to propound a general knowledge structure.

Throughout the thesis, the implications for teaching have been discussed for all the studies. The questionnaires and free card sorting exercises both point towards content learning and classification. A change to a conceptual form of teaching is strongly recommended in all the studies. The future will show whether the recommended approach to teaching and learning will help in modifying the knowledge structure of the students.

Appendix A

Published papers

A.1 Geometrical Optics: Knowledge of Students

This paper was published in the proceedings of the Asia Physics Education Network Conference and Workshop on the Teaching of Optics held in Melbourne, Australia from 23-27 September 1989.

Geometrical Optics: Knowledge of Students

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1 Introduction

In many countries the teaching of geometrical optics in schools is being constantly reduced and replaced by the teaching of electromagnetic wave theory. This has resulted in a low knowledge and understanding of geometrical optics amongst students enrolling in first year university physics courses.

Geometrical optics is being taught at the lower secondary levels where it cannot be covered in any great depth due to the lower maturity level of the students. This earlier approach to geometrical optics is also being made along very experimental lines. Students know the phenomena they observe but at this level it is difficult to implant a sound conception of the physical reasoning involved. Thus the subject matter is covered as content rather than concept. A series of experiments are performed and observations made, but the application of physical theories to provide the underlying explanation for the phenomena observed is often neglected. As the student progresses from his first introduction to the subject in lower secondary through to undergraduate level, there is no continuity.

2 Changing Trends

In the sixties geometrical optics was taught at all levels in New Zealand and Singapore secondary schools. From the seventies the syllabus was constantly modified. The trend in both countries has been the transference of geometrical optics teaching to the junior level and the introduction and expansion of wave optics at the senior level.

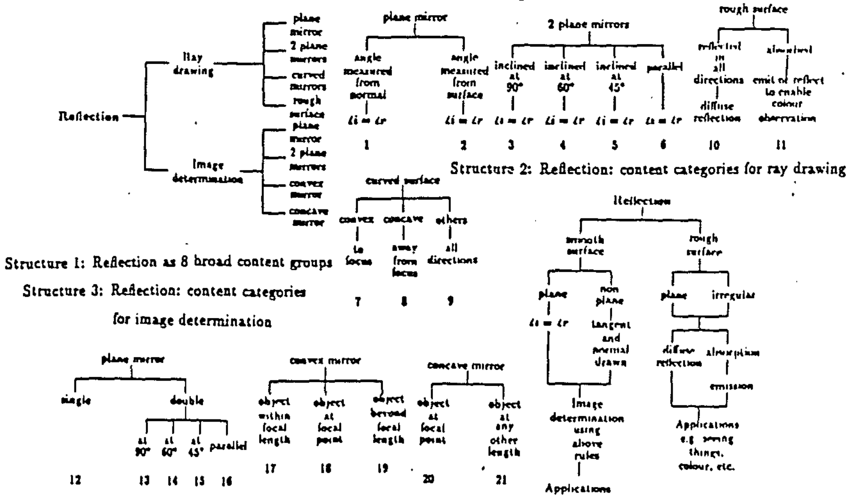
2.1 New Zealand

In the late seventies the geometrical optics syllabus at the Forms [1] 1 to 4 level was replaced by a module entitled radiant energy. This structured the teaching of geometrical optics at the junior level. Over the last decade geometrical optics has been totally replaced with wave optics in the university bursary prescription. Since the early eighties, with the option of internal assessment for Form 5 science, many schools started teaching a new module entitled energy. This module does not include any geometrical optics. In 1985, the university entrance examination for Form 6 was discontinued. Quite a few schools have since geared their Form 6 syllabus to be in tune with the Form 7 bursary prescription by replacing the geometrical optics component with wave optics. However, some of these schools do have experiments on geometrical optics as part of their laboratory course.

[1] Forms 1 to 4 age group: 12 to 15 years; Forms 6 and 7 age group: 16 to 18 years

2.2 Singapore

Until the late seventies, geometrical optics featured prominently at all levels of secondary [2] science teaching. In 1983 it was totally removed from the pre-university syllabus and incorporated into the secondary 3 and 4 syllabus. However, experiments on geometrical optics are still part of the pre-university laboratory course. Presently, in secondary 1 and 2 only geometrical optics is taught, in secondary 3 and 4 both geometrical and wave optics are taught and at the pre-university level only wave optics is taught. The geometrical optics knowledge of students leaving school depends on the science subject they read in secondary 3 and 4. Those reading physics would have the greatest depth of exposure, next would be those reading physical science followed by those reading general science.



Structure 1: Reflection as 8 broad content groups

Structure 2: Reflection: content categories for ray drawing

Structure 3: Reflection: content categories for image determination

Structure 4: reflection as a concept

3 Content or Concept

To many students, geometrical optics is a conglomeration of independently existing topics. The content they learn is characterised by group membership using surface features. (see structures 1,2 and 3)

When faced with a certain set up, students were able to answer only if the situation fit a content group in their minds. To them there exist roughly as many topics as are examples with different surface features. Very few students were able to generalise and apply the idea learnt.

Students form categories to make sense of the subject matter learnt. It is their way of simplifying the content. This is the first step towards concept formation. If surface features are used then the categories become situational and the subject matter is not learnt as a concept. For concept formation to result, categories developed must have rules and conditions. These rules need to be highlighted each time any subject matter related to the concept is discussed. In simplifying the subject matter when teaching, it is easier to refer to situation- specific rules and to use common labels. These create different cues in the minds of students and sets them categorizing without concept in mind. Structure 4 shows a guideline which could be used to teach students to relate different situations of the same concept. Only the name and rules of the concept are mentioned. Mention of surface features is avoided.

[2] sec. 1 to 4 age group: 12 to 15 years; pre-university age group: 16 to 17 years

Questionnaire Group	1	2	3	4	5	6	7	8
A	18.9 (6)	3.3 (5)	29.2 (6)	42.9 (7)	20.6 (6)	3.9 (7)	7.4 (8)	7.9 (7)
B	34.4 (3)	39.1 (4)	47.5 (5)	−61.1 (6)	52.3 (3)	68.1 (9)	41.0 (9)	41.7 (10)
C	60.0 (4)	30.5 (7)	60.4 (6)	56.1 (9)	58.5 (7)	55.5 (10)	52.1 (6)	48.9 (5)
D	48.9 (6)	24.5 (6)	66.7 (5)	61.6 (6)	61.5 (6)	9.1 (6)	57.3 (6)	40.7 (6)
E	56.3 (8)	48.0 (8)	60.9 (8)	69.3 (8)	49.6 (8)	56.5 (8)	49.6 (5)	43.1 (8)
F	60.6 (6)	43.5 (6)	66.7 (5)	73.0 (5)	53.3 (5)	44.5 (5)	64.4 (5)	42.2 (5)

*(parenthesis indicate number of students)

Table 1: Percentage scores of the various groups in each questionnaire

Students need to be trained to fit content they learn into the structure of related concepts. These general steps could be repeatedly used to teach the students a concept:

- giving the concept a name
- stating and discussing the rules determining membership of content in a concept
- stating any special conditions or rules within the concept by which the content needs to be tested for specific classification within the structure of the concept
- applying the rules and conditions to many different situations to teach the application of the concept. Situations where the concept is not applicable also need to be included since part of knowing a concept is recognizing instances when the content does and does not fit into the concept

4 Knowledge of students

Eight questionnaires covering: (1) terms used in geometrical optics; (2) equations used in geometrical optics: (3) general notions on light; (4) reflection at plane surfaces: (5) refraction; (6) reflection at curved surfaces (mirrors); (7) refraction with lenses; and (8) refraction with prisms. These were administered to the following groups: (A) form 5 students; (B) form 6 students; (C) form 7 students; (D) pre-university 1 students in Singapore; (E) year one New Zealand undergraduates reading physics; and (F) year one foreign undergraduates reading physics in New Zealand. (see table 1)

4.1 Terms in geometrical optics

Students were asked to explain their understanding of 15 terms they encounter in the learning of geometrical optics. The images formed by convex and concave mirrors and lenses was least understood and remembered by students. Answers for the terms principal focus. laws of reflection. refraction and refractive index showed a lack of depth in students knowledge. They knew the terms superficially and could not specifically explain them. Principal focus was attributed to mirrors or lenses and not to both. Students knew that the angle of incidence equals the angle of reflection but did not mention that the incident ray, the reflected ray and the normal at the point of incidence

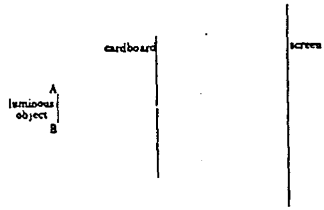


Figure 1: Image determination using a pinhole

lie in the same plane. Only 2 out of 33 knew that refraction was due to the change in speed of light in different media. Most defined refraction as the bending of light or a change in its direction as it went from one medium to another. Many were unable to reconcile the fact that refraction took place at normal incidence as well. They stated it as a special case or disregarded it as refraction. Only 5 out of 33 defined refractive index as the ratio of the velocity of light in vacuum or air to that in a medium, 9 defined it as the ratio of the sine of the angle of incidence to the sine of the angle of refraction and the other 19 were unable to define it.

4.2 Equations used in geometrical optics

Students were asked to state the meaning of symbols used in eight equations and to mention the conditions under which the equations were applicable. The two equations which more students recognised were (i) $\angle i = \angle r$ for reflection which 31 out of 36 stated correctly, but only 17 knew the conditions of its applicability; and (ii) $n = \sin i/\sin r$ for refraction from air or vacuo into a medium which 18 out of 36 stated correctly, but only 5 managed to correctly state the conditions for its applicability. The Form 5 students had no knowledge of any equation except $\angle i = \angle r$. The interesting find was that none of the 11 foreign students knew the equations $S_i S_o = f^2$ and $H_i/H_o = S_i/f$. Apparently, these two equations are not studied in their countries. They knew the equation $1/v + 1/u = 1/f$, which many New Zealand students did not recall.

4.3 General notions on light

Most students loosely knew the answer to the question, *What is light?*. When asked to be specific apart from *it is a form of energy* students referred to light mainly in terms of generation, nature, properties and components. When asked to explain regular and diffuse reflection many students could not specifically do so. They were unable to state the conditions under which these two types of reflection took place. Many used a plane mirror to explain the two terms stating that in regular reflection no absorption took place while in diffuse reflection part of the incident light was absorbed and hence only partially reflected.

Another question asked was, *Is light always transmitted, reflected or absorbed? Explain.* Even after being told that they were being asked about the simultaneity of occurence of the three processes only 6 out of the 35 students managed to relate the three processes. Most thought that only one process occurred each time.

Students were asked to state the difference in brightness of the images if another pinhole was made in the cardboard in Figure 1. Even those who answered correctly could

Group	A	B	C	D	E	F
Reflection of a single plane surface	92.9	90.0	55.9	53.3	100	100
Reflection of two plane surfaces	35.7	66.7	66.7	73.2	73.0	50.0
Reflection of a single curved surface	9.5	35.9	23.9	53.0	33.3	46.7
Image determination in a single plane mirror	0.0	30.0	55.5	55.3	12.5	60.0
Image determination in a single curved mirror	0.0	55.0	63.3	2.5	30.0	33.3

Table 2: Percentage scores on reflection tasks

not give a substantial explanation. Those who took the pinholes too close together and obtained overlapping images gave the following answers (i) the brightness in the overlapping region would be double while that in the other region would be equal; or (ii) the brightness in the overlapping region would be equal while that in the other region would be half. Many drew the images distinctly separated stating that the brightness would be halved. Some senior students drew interference patterns. When asked for an explanation they stated, *There are two openings close together.* They had no idea of the conditions necessary for obtaining interference.

4.4 Reflection

Students were asked to (i) trace the paths of rays incident on single plane and curved reflecting surfaces; (ii) determine the positions of images produced by single plane and curved mirrors using ray drawings; and (iii) determine the number of images formed by two plane mirrors. (see table 2)

Most students were able to accurately trace and explain the path of a ray reflected off a single plane surface. For two plane surfaces inclined at an angle to each other, students had difficulty in drawing the path of the reflected ray. More students drew the path of the ray correctly for the mirrrors inclined at 90°. They were more familiar with the 90° set up as many textbooks use it as an example.

Students performed poorly in determining image positions through ray tracing. The variation in scores within each group indicate that students do not apply the general concept of reflection. They treat concave, convex and plane mirrors as distinctly different with different rules for determining image positions by ray tracing. All three are not seen as encompassed within the single concept of reflection.

Students were unable to accurately determine the number of images formed for two mirrors (a) inclined at an acute angle to each other and (b) placed parallel to each other.

The scores were much lower than those for the case of image determination with a single plane mirror. This again points to the inability of the students to apply the same concept in different situations.

4.5 Refraction

Students were asked to (1) state their understanding of refraction and the conditions under which it takes place; (2) complete the path of rays incident on a plane interface from a lighter to a denser medium and vice-versa; (3) complete the path of rays incident on a curved interface; (4) complete the path of rays through a medium with non parallel interfaces, namely prisms.

Group	A	B	C	D	E	F
Understanding of refraction	33.3	70.0	92.9	100	87.5	90.0
Rays incident on a plane interface:lighter to denser	29.2	82.5	94.7	93.3	78.6	92.5
Rays incident on a plane interface:denser to lighter	23.3	55.0	60.7	50.0	37.5	35.0
Rays incident on a curved interface	0.0	10.0	0.0	5.6	16.7	26.7
Rays through prisms	7.9	14.7	48.9	40.7	43.1	42.2

Table 3: Percentage scores on refraction tasks

In all the cases only the general rules governing refraction were needed except for a ray incident in a denser medium, where the incident angle had to be compared to the critical angle of the medium to determine the occurence of refraction or total internal reflection. The percentage scores (see table 5) indicate that students encounter difficulty in applying the same concept to situations with different surface features. Only a handful drew normals at the points of incidence to determine the path of the refracted ray. They seem to remember the paths of refracted rays through the use of surface features e.g. concave, convex, plane, semicircular block, equilateral prism, 45° isosceles prism, etc. The orientation between the ray and the medium affected the answers as well. Set pieces were memorised and applied to other foreign situations without understanding the actual process involved. The lack of ancillary knowledge of the concept results in ambiguity of application.

A case of learning by rote without understanding the concept was portrayed in the drawing of the dispersion effect in prisms. When drawing rays through rectangular and semicircular glass blocks the dispersion effect was not considered but for prisms many drew the dispersion.

5 Implications for teaching and learning

To improve the geometrical optics knowledge of students, concept teaching needs to be stressed. Content is important but it should be used as a means of concept attainment. In simplifying the subject matter, educators are sometimes guilty of subdividing the concept and teaching it in small labelled content portions. Learners in turn use these labels to categorize without relation to the concept. Consequently when answering applications questions, the students do not apply the principle involved but search through their memory bank for content they have covered. If the content does not exactly fit the question under consideration then they are at a loss. They answered *set pieces* much better. Set pieces for example generation are a step towards the learning of a concept but just these without any rules and ancillary information will not do much good for understanding and application of the concept. It was noted that many who have the knowledge and knew the answers to the questions were unable to provide sufficient explanation. Attention to finer detail was also lacking as students understanding lacked depth.

The syllabus needs to be changed to make the teaching of geometrical optics progressive. Reflection is used as an example to illustrate this. At present, the learner is exposed to all facets of reflection each year. The different facets of reflection could be subdivided and taught as follows

Year 1 reflection, ray tracing and image determination for a smooth plane surface.

Year 2 As in year 1 using two or more plane reflecting surfaces.

Year 3 reflection and image determination for curved surfaces.

Year 4 reflection and image determination for various shaped surfaces.

Year 5 grazing reflection for smooth surfaces of various materials.

In each successive year, the syllabus covered in the preceding years should be used as an introduction to the next level. This will serve to refresh the mind and make obvious the connection between the various components. With the development of a progressive syllabus greater depth might ensue.

Acknowledgements

I wish to thank all the teachers and students who in some way or other participated in the collection of data.

References

[1] U. E. Board. University entrance and bursary prescription. *Universiy of Canterbury Handbook*, 1960 to 1989.

[2] D. of Educ. School cert. physics. *The Education Gazette*, 15 Nov 1979.

[3] M. of Educ. Syllabus for secondary schools. *Syllabus for Science*, 1960 to 1990.

A.2 The Science Roadshow 1988: The effects on pupils

This paper was published in the NZ Science Teacher (issue 61).

THE SCIENCE ROAD SHOW 1988 : The effects on pupils

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In November 1987 an enthusiastic sub-committee of the Canterbury Science Teachers' Association (CSTA) organised a very successful and popular *Science—Technology Extravaganza*. There were over 14,000 visitors (9000 school children) in the five days it was open and with more requests for visits from schools than could be accommodated (numbers were restricted to allow all to have ready access to exhibits). The emphasis was on "hands-on" scientific exhibits and it was obvious that they captured the interest of a wide age-group, but especially the Form 1 to 4 school pupils. The popularity and success of the *Extravaganza* prompted the Minister of Science and Technology Mr Tizard, to suggest that part of the show be put on the road and taken to as many areas of the South Island as would be practicable.

Planning began for a *Science Road Show* in January and once the funding of the two major costs (a seconded teacher and transport) had been established a detailed itinerary was organised to cover as much of the South Island as possible in the eight weeks available. Pupils from Collingwood to Bluff at the *Road Show* was evidence that the net had been spread far and wide. The assistance offered by the Ministry of Defence in its venture was not only generous, but critical to its success. A large articulated trailer and tractor unit capable of transporting nearly 70 cubic metres of equipment allowed a wide range of scientific themes to be covered (e.g. Chemistry, The Earth, Mechanics, Living Things, Electricity, Light) as well as providing space for the substantial Physics and Chemistry demonstration apparatus (e.g. a Tesla coil, chemical benches, gas cylinders etc.). An army driver and all vehicle costs were supplied without charge (the actual transport costs totalled around $18,000) and this enabled the entrance fee for pupil to be kept to a minimum ($1).

The format used in the *Road Show* was such that it could be used more as a teaching forum than had been the case with the "trade-fair" approach of the Extravaganza. A typical session involved a chemical demonstration illustrating energy changes (colour, light, sound) in a selection of spectacular experiments. This lasted about 15 minutes after which the pupils were invited to play with the exhibits that had been set up in the large part of a hall. Our message was 'do touch' *not* 'don't touch' and this alone was enough to entice the more reluctant types. Senior pupils from high schools in each centre acted as explainers and demonstrators for the exhibits. Almost without exception, the explainers took to their jobs with great vitality and enthusiasm. Besides learning some new scientific material, the seniors learnt some important lessons in teaching and communication. This was one of the great bonuses of the *Road Show*. Playtime for the audience lasted approximately 45 minutes. The final act in each session was a 10 minute physics demonstration showing spectacular releases of electrical energy and charges of state.

The primary objective of the *Science Road Show* was to stimulate a greater interest and awareness in science particularly in the Form 1 to Form IV age-group.

Many letters have been received from teachers subsequent to the *Road Show* visiting them, indicating that the pupils' level of understanding and appreciation of science had been enhanced.

An objective assessment on the effect of the *Road Show* on pupils was attempted in the form of a simple questionnaire administered to a sample of the children who visited the *Road Show*. The questionnaire was administered both before and after the Road Show. The results of the survey follow.

The Director of the *Science Road Show*, Tim Oughton, did not anticipate the enthusiasm and popularity generated amongst pupils, teachers and the general public. As Science teachers we must *make* every endeavour to keep the profile of our subject high if NZ is to further develop its technological and scientific base. The *Science Road Show* helped achieve this and as a support to science teachers it must continue.

Questionnaire

A questionnaire[1] was administered to the Form 1 to 4 children from eight schools prior to attending the Road Show. The questionnaire was readministered to the same children after the show. The questionnaire was divided into three main sections, namely:

1. ATTITUDES SCALE: Where students were required to choose three subjects from a total of seven and categorise them as first, second and third choice.

2. WHAT I LIKE: Eight multiple choice questions were included to determine how much the students liked science topics in comparison to others.

3. INTEREST IN SCIENCE: Twenty four questions were answered by students to test their level of interest in topics on science.

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[1] 1: See Appendix 1. 2: See Appendix 2. 3: See Appendix 3.

SCORING

1. ATTITUDES SCALES: Only the science choice was taken in to account. 1 was scored for the first choice, 2 for the second choice, 3 for third choice, and 4 if science was not chosen as one of the three choices.

2. WHAT I LIKE: 1 was scored for choosing a science related topic and 0 for any other choice. The score for the eight questions was totalled.

3. INTEREST IN SCIENCE: 0 was scored for the "Not at all" choice, 1 for the "once or twice" choice. The score was totalled over the twenty four questions.

STATISTICAL TEST

The comparisons have been divided into three families, namely:
1. Family 1: Main effect for all scores
2. Family 2: Main effect nested in sex, and
3. Family 3: Main effect nested in form level.

FAMILY 1: The paired sample t-test was used. Table 1 gives the significant contrast.
FAMILY 2: A one-way analysis was done using only five contrasts of interest. The significant contrasts are shown in Table 2.
FAMILY 3: Nineteen contrasts of interests were carried out using the one-way analysis of variance by form level. The significant contrasts are shown in Table 3.

Each family has been further subdivided into 3 sections, namely:
1 Attitudes scale; 2. What I like, and 3. Interest in Science
All one-way analysis of variance contrasts were done using the separate variance estimate.

INTERPRETATION

FAMILY 1: MAIN EFFECTS FOR ALL SCORES.

1. ATTITUDES SCALE: There was no significant change in numbers of students choosing science as one of their first three choices.

2. WHAT I LIKE: This contrast was of a significant difference. The scores after the show portrayed a significant decrease. This may be attributed to the various interests of students in today's world.

3. INTEREST IN SCIENCE: There was no significant change in the scores of students.

FAMILY 2: MAIN EFFECT NESTED IN SEX.

There was no change in all three sections between boys or girls before and after the show. However, there was a significant difference between boys and girls prior to the show. This difference remained even after the show. The girls had a significantly higher score for the attitudes scales, indicating that more boys chose science as the first three choices in comparison to girls. This supports the general belief that girls tend to shy from science in comparison to boys.

After the show, the girls' scores for "Interest in Science" rose significantly in comparison to the boys. Prior to the show there was no significant difference between the scores of boys and girls. It can be concluded that after the *Road Show* the girls definitely showed a rise in "Interest in Science".

FAMILY 3: MAIN EFFECT NESTED IN FORM LEVEL

1. ATTITUDES SCALES: Before the *Road Show* there was a significant difference in scores of Form 4 students in comparison to Forms 1 and 2 combined. The Form 4 students scored significantly less, showing that more of them made one of the first three choices as science in comparison to Forms 1 and 2 students. This could be due to the larger exposure that Form 4 students acquire over a greater number of years. The Form 1 and 2 students on the other hand are just beginning to be exposed to secondary science. The Forms 3 and 4 combined showed a significantly lower score in comparison to the Forms 1 and 2 combined. However, after the Road Show, these significant differences disappeared. This could be that the exposure of the Forms 1 and 2 to the Road Show created a change in attitudes and more chose science as one of their first three choices.

2. WHAT I LIKE: There was a significant difference in scores of Form 1 students prior to and after attending the Road Show. The scores increased significantly showing that Form 1 students had been positively affected to become more science bias.

   The Forms 1 and 2 combined scored significantly higher than the Form 4 students, both prior to and after the show. This may be attributed to the larger scope of interest of the fourth-formers and to their larger and more varied exposure to more subject areas.

   There was a significant difference between the first and second-formers combined in comparison to the third-formers after seeing the show. The scores were significantly higher for the Forms 1 and 2 combined. Furthermore, after the show, the Forms 1 and 2 combined scored significantly higher than the Forms 3 and 4 combined. This points again to the benefit attained by Forms 1 and 2 (especially Form 1) students after the *Road Show*. The juniors seems to benefit more from the exposure to the show.

3. INTEREST IN SCIENCE: There was no significant differences in scores for any of the comparisons. Hence, the Road Show did not have any significant effect on the scores of students.

IMPLICATIONS

A. FOR THE ORGANISERS:

The survey quite conclusively shows that Forms 1 and 2 students experienced a positive change in attitude towards science. The exhibits at the *Road Show* must have appealed to them. The survey did not show an increase in the interest of the third and fourth formers. It may be that the organisers need to include more exhibits at this level or it may be that the student interest was high beforehand. The organisers may wish to rethink some of the exhibits so as to make the *Road Show* attractive to senior students as well. The questionnaire did not try to identify which features of the exhibits were successful. It is our intention to perform a more detailed study during this year's forthcoming Road Show. Mr Peter Richards of Riccarton High School is the Director of the 1989 CSTA *Road Show*.

B. FOR SCHOOLS AND TEACHERS:

The *Road Show* provides a novel opportunity for students to experience science. The students are able to learn through hands-on involvement provided by the variety of exhibits which tries to cater to the interests of most students. Furthermore, Forms 1 and 2 students and girls showed an increase of interest in science through participation in the *Road Show*. This should provide encouragement to schools and teachers in their efforts to promote science in schools. We hope that this success will also signal more schools to participate in future *Road Shows*. If interest in science can be successfully increased in the early stages amongst children, then we will be successful in promoting science in our schools.

ACKNOWLEDGEMENTS

We would like to thank the following for assistance with the survey:

(i) Professor Warwick Elly, Education Department at the University of Canterbury for helping to design the questionnaire.
(ii) Mr John Longbottom, Education Department of Christchurch Teachers' College, and
(iii) all school teachers who participated in the survey.

APPENDIX 1

A typical *Road Show* programme

Each visit "slot" is 75 minutes. In this time there will be:

- A "chemical" demonstration (10 mins) illustrating spectacular changes (colour, light, sound) in a selection of experiments.
- A "physics" demonstration (10 mins) showing spectacular releases of electrical energy and changes of state.
- at least 20 "hands on" exhibits (chosen from the following list) illustrating a wide variety of scientific themes.

The Earth
Geological jigsaw
Domesday project
Earthquake response
Radiation
Gamma level gauging

Chemistry
Exploding flask
Brownian motion

Mechanics
Bernoulli blower
Bernoulli balls
Hopper
Fluidisation
Harmonograph
Rotating Chair
Reaction Tester
Bed of Nails
Gearbox display
Resonance in a rod

Heat
Heat pipe
Convection currents

Living things
Roots meet soil
Medical
Live animals

Electricity
Hand battery
Co-ordination tester
Visible speech
'Fleas'
Van de Graaff
Magnetic repulsion

Light
Stress polarisation
Peripheral vision
Roses (mirror)
Persistence of vision
Coloured shadows
Tricky tap

APPENDIX 2

QUESTIONNAIRE

Name: Class:

School: Boy or Girl:

ATTITUDES SCALE

Which of these subjects do you like best at school?

Write 1 beside your first choice, 2 beside your second and 3 beside your third choice.

Art	
Mathematics	
Music	
Reading	
Science	
Social Studies	
Writing	

WHAT I LIKE

Choose the activity you like most in these sets of three. Write the letter of your choice on the right. There are no right or wrong answers.

1. Which of these things would you rather read about?
   A Strange insects
   B Musicians
   C Famous explorers ________

2. Which of these things would you rather do?
   A Play with a pet
   B Play video games
   C Collect rocks and shells ________

3. Which of these you would prefer to watch a video about?
   A Exploring the bottom of the ocean
   B Travelling through China
   C The early history of your country ________

4. Which would you rather be when you grow up?
   A A writer
   B A lawyer
   C A scientist ________

5. Which of these would you rather hear a story about?
   A Riding horses
   B Travelling in outer space
   C The life story of a famous sports personality ________

6. If you visit the museum, which section would you prefer to spend most time in?
   A Early history of your region
   B The bird or animal collection
   C The Polynesian ________

7. If you had to choose a book for a gift for yourself, what book would you choose?
   A Lost in the Forest
   B A Mystery Solved by Science
   C Chased by a Bull ________

8. Which school lesson would you be most interested in?
   A How electricity works
   B What the first English settlers found in NZ
   C Why we need to pay taxes ________

INTEREST IN SCIENCE

In the past month, how often have you done the following? Place a tick under one of the three choices.

	Not at all	Once or Twice	More than Twice
1. Read newspaper article about scientific things	______	______	______
2. Experimented with or repaired battery toys, "walkie-talkies" or model cars	______	______	______
3. Tried to tell weather by clouds, temperature	______	______	______
4. Made drawings or models of earth, planets, moon	______	______	______
5. Looked up ways to use home chemistry set	______	______	______

	Not at all	Once or Twice	More than Twice
6. Thought about origin of living things	_____	_____	_____
7. Worked on collecting rocks and minerals	_____	_____	_____
8. Read stories about volcanoes, earthquakes, or mountains	_____	_____	_____
9. Read about the lives of scientists	_____	_____	_____
10. Watched scientific programs on TV about wild animals	_____	_____	_____
11. Talked with an adult outside school about science	_____	_____	_____
12. Observed flowers or watched plants grow	_____	_____	_____
13. Used microscope to examine plants or animals	_____	_____	_____
14. Watched explanation of weather on TV	_____	_____	_____
15. Experimented with vinegar, salt, sugar — common things in the home	_____	_____	_____
16. Made oral or written reports about science	_____	_____	_____
17. Thought about origin of the earth, sun, stars	_____	_____	_____
18. Read about heat, sound, light	_____	_____	_____
19. Watched and studied wild animals and birds	_____	_____	_____

	Not at all	Once or Twice	More than Twice
20. Thought about pollution	______	______	______
21. Put out food for wild birds	______	______	______
22. Wondered about why cakes rise	______	______	______
23. Looked at science books in libraries	______	______	______
24. Made models and equipment out of ordinary things	______	______	______

APPENDIX 3 : LIST OF PARTICIPATING SCHOOLS

Name of School	No. of Students		
	Boys	Girls	TOTAL
1. Abbotsford	12	15	27
2. Ashburton College	13	13	26
3. Balmacewan Intermediate	16	11	27
4. Broadgreen Intermediate	2	3	5
5. Central Southland College	10	14	24
6. Green Island	10	20	30
7. Motueka High School	3	2	5
8. St Peter's College	10	7	17
TOTAL	76	85	161

TABLE 1 : SIGNIFICANT CONTRAST FOR FAMILY 1

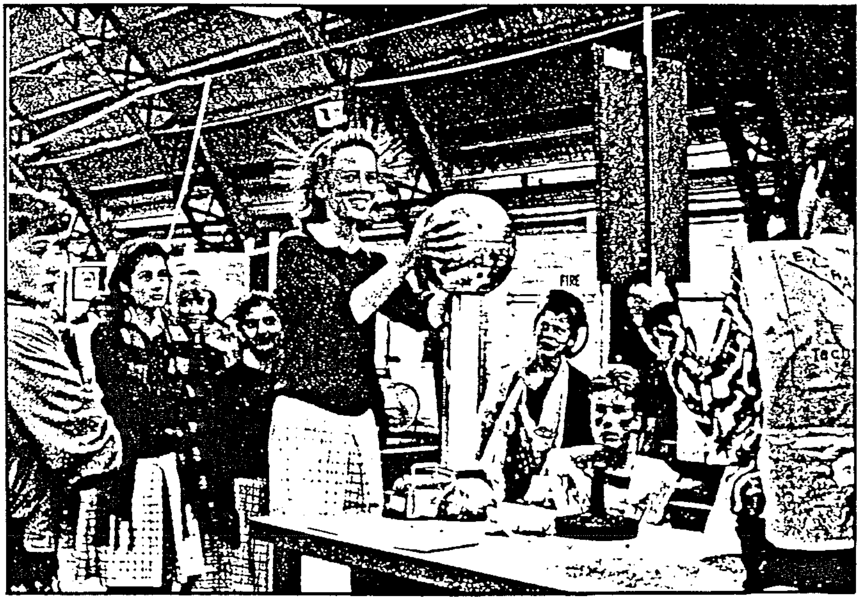
	WHAT I LIKE		
	Pre Score	Post Score	Contrast No.
	-1	1	1
MEAN	3.30	3.62	
SIZE,N	161	161	

TABLE 2 : SIGNIFICANT CONTRASTS FOR FAMILY 2					
	BEFORE		AFTER		
	Boys	Girls	Boys	Girls	Contrast No.
ATTITUDES SCALE	1	-1	0	0	2
	0	0	1	-1	3
MEAN	2.55	3.36	2.59	3.13	
SIZE,N	76	85	76	85	
INTEREST IN SCIENCE	0	0	1	-1	4
MEAN	16.41	16.48	15.01	18.87	
SIZE, N	76	85	76	85	

TABLE 3 : SIGNIFICANT CONTRASTS FOR FAMILY 3									
	BEFORE				AFTER				
	F.1	F.2	F.3	F.4	F.1	F.2	F.3	F.4	Contrast No.
ATTITUDES SCALE	-1	-1	0	2	0	0	0	0	5
	-1	-1	1	1	0	0	0	0	6
MEANS	3.00	3.27	2.98	2.17	2.75	3.13	2.93	2.33	
WHAT I LIKE	-1	0	0	0	1	0	0	0	7
	-1	-1	0	2	0	0	0	0	8
	0	0	0	0	-1	-1	2	0	9
	0	0	0	0	-1	-1	0	2	10
	0	0	0	0	-1	-1	1	1	11
MEANS	3.50	3.33	3.42	3.89	4.23	3.75	3.40	2.61	
SIZE, N	40	48	55	18	40	48	55	18	

TABLE 4 : DETAILS OF ALL SIGNIFICANT CONTRASTS					
CONTRAST NO.	CONTRAST	STD.ERROR S.E.	t-VALUE	CONFIDENCE Lower Limit	INTERVAL Upper Limit
1	-0.323	0.104	-3.10	-0.494	-0.152
2	-0.810	0.176	-4.60	-1.10	-0.520
3	-0.540	0.189	-2.86	-0.851	-0.229
4	-3.86	1.57	-2.45	-6.44	-1.28
5	-1.93	0.505	-3.82	-2.79	-1.07
6	-1.12	0.368	-3.04	-1.73	-0.508
7	0.730	0.345	2.12	0.151	1.31
8	-2.05	0.748	-2.74	-3.59	-0.512
9	-1.18	0.553	-2.13	-2.10	-0.264
10	-2.76	0.837	-3.30	-4.19	-1.33
11	-1.97	0.560	-3.52	-2.90	-1.04

Many institutions provided exhibits and staff that gave new experiences to people of all ages.
Here Professor Boswell of the Christchurch Clinical School, explains an electrocardiograph. (Photo taken at the second (1988) Extravaganza).



Electrostatics is always a hair-raising experience.
Senior pupils enjoy their role as explainers.

Magnetic stirrers, causing vortexes in liquids of different viscosity, were a source of fascination.

Appendix B

Questionnaires on Optics

The optics questions used for data collection are included in this section. Beneath each question spaces were provided for the answers. The questionnaire titles were not included in the actual questionnaires.

B.1 Terms used in Geometrical Optics

You will have met many of the following terms in your science learning. Please provide a detailed explanation for each of the terms. You may put forth more than one explanatory answer for each.

1. Concave lens
2. Convex lens
3. Refraction
4. Laws of Reflection
5. Concave mirror
6. Convex mirror
7. Centre of Curvature
8. Principal focus
9. Refractive Index
10. Total Internal Reflection
11. Critical Angle
12. Images formed by a concave mirror
13. Images formed by a convex mirror
14. Images formed by a concave lens
15. Images formed by a convex lens

B.2 Equations in geometrical optics

You will have met many of the following equations in your science learning. For each equation, could you please
(i). explain the meaning of the algebraic symbols; and
(ii). state the conditions for its applicability.

If an equation is totally unfamiliar to you, please say so, and continue with the others.

1. $$\text{Angle } \mathbf{i} = \text{Angle } \mathbf{r}$$
(i). Meaning of symbols.
(ii). Conditions for applicability.

2. $$n = \frac{c}{v}$$
(i). Meaning of symbols.
(ii). Conditions for applicability.

3. $$n = \frac{1}{\sin c}$$
(i). Meaning of symbols.
(ii). Conditions for applicability.

4. $$n = \frac{\sin i}{\sin r}$$
(i). Meaning of symbols.
(ii). Conditions for applicability.

5. $$n_1 \sin\theta_1 = n_2 \sin\theta_2$$
(i). Meaning of symbols.
(ii). Conditions for applicability.

6. $$S_o S_i = f^2$$
(i). Meaning of symbols.
(ii). Conditions for applicability.

7. $$\frac{H_i}{H_o} = \frac{S_i}{f}$$
(i). Meaning of symbols.
(ii). Conditions for applicability.

8. $$\frac{1}{v} + \frac{1}{u} = \frac{1}{f}$$
(i). Meaning of symbols.
(ii). Conditions for applicability.

B.3 General notions on light

Answer all the questions, providing detailed explanations for each answer. If you feel a question is ambiguous, explore and provide answers for all the possibilities. The spaces provided for the answers are not indicative of the length of the answer.

1. What is light ?

2. Why are shadows formed ?

3. How are we able to see objects that do not emit their own light ?

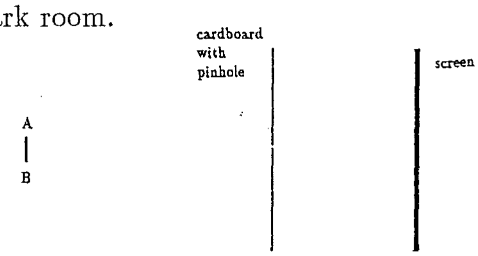
4. Why are some images considered real while others are considered virtual ? reflection

Explain the following types of reflection stating the conditions under which it occurs:

(a). Regular Reflection

(b). Diffuse Reflection

6. The diagram below shows an arrangement to obtain the image of a bright source AB on a screen in a dark room.



(a). State the factors affecting the size of the image formed on the screen.

(b). Use rays to determine the position of the image on the screen.

(c). How will a larger pinhole affect the image formed ? Explain.

(d).Another pinhole is made in the cardboard. What will be seen on the screen ? Draw a ray diagram to explain the observation.

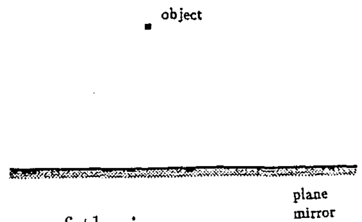
(e). Compare the brightness of the images in (b) and (d).

7. Is light always transmitted, reflected or absorbed ? Explain.

B.4 Reflection at plane surfaces

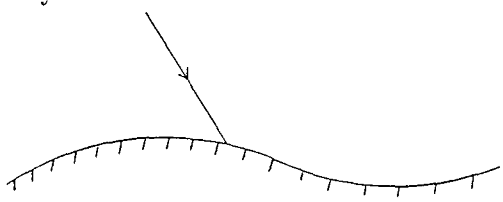
Answer all questions, providing detailed explanations for each answer. If you feel a question is ambiguous, explore and provide answers for all the possibilities. The spaces provided for the answers are not indicative of the length of the answers.

1.(a). Use rays to find the position of the image formed by the plane mirror.



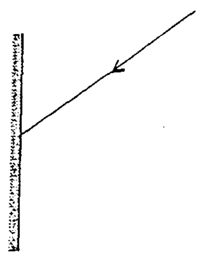
(b). Describe the nature of the image.

2. A ray is incident on the reflecting surface shown below. Determine the direction of the reflected ray.

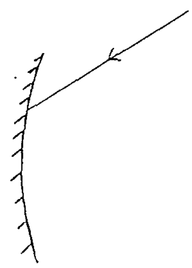


3. Show the path of the ray after reflection, for each of the following. Provide an explanation for each answer.

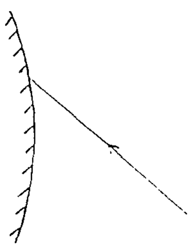
(a).



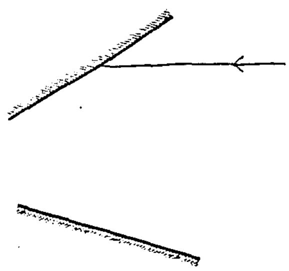
(b).



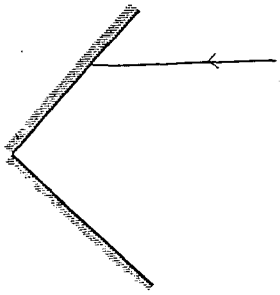
(c).



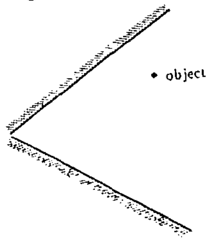
(d).



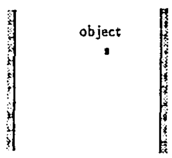
(e).



4. An object is placed between two plane mirrors as shown in the diagram below. State the number of images that will be formed. Justify your answer.



5. The diagram below shows an object placed between two parallel plane mirrors. State the number of images that will be formed. Explain your answer.



B.5 Refraction

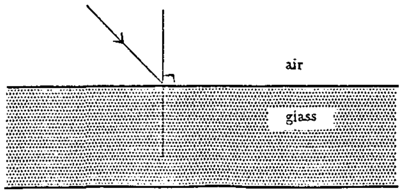
Answer all the questions, providing detailed explanations for each answer. If you feel a question is ambiguous, explore and provide answers for all the possibilities. The spaces provided for the answers are not indicative of the length of the answer.

1.(a). What is refraction ?

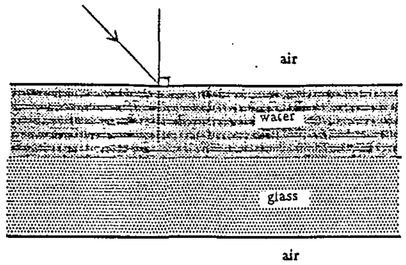
(b). When does it take place ?

2. Complete the following ray diagrams showing all the possible directions of the rays. Provide an explanation for each answer.

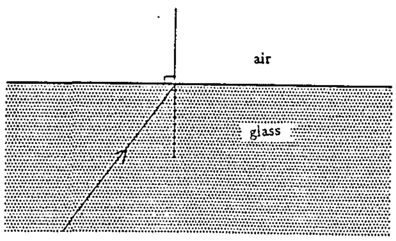
(a).



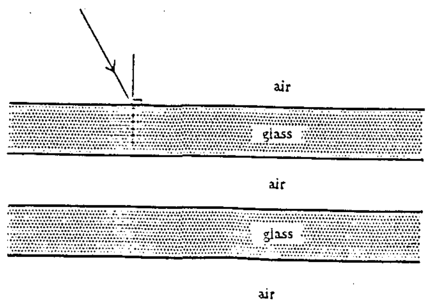
(b).



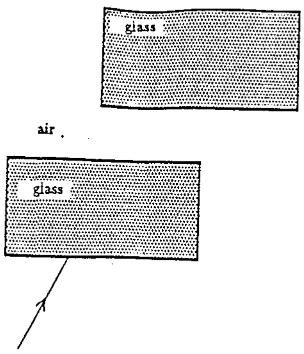
(c).



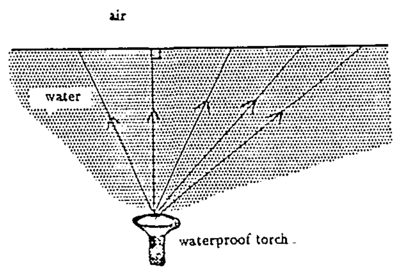
(d).



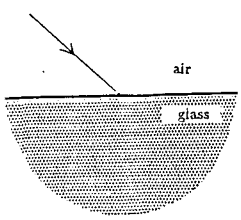
(e).



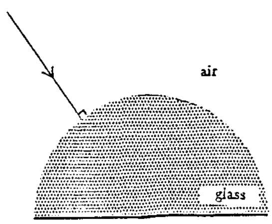
(f).



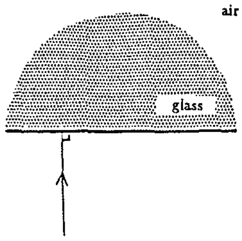
(g).



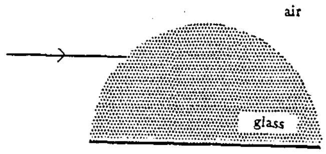
(h).



(i).

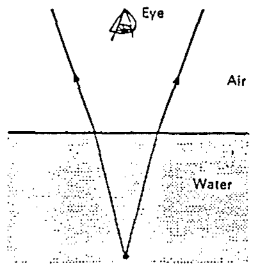


(j).

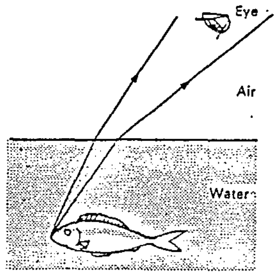


3. Complete the following ray diagrams to locate the position of the image.

(a).

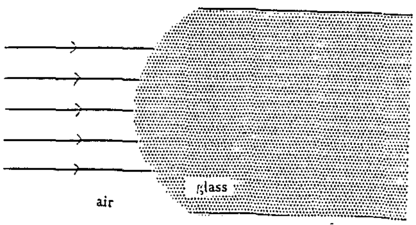


(b).

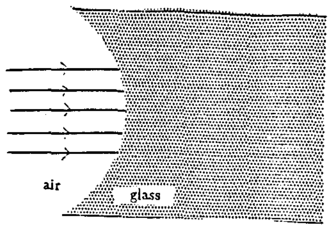


4. The diagrams given below show rays of light incident on an air-glass interface. Complete the ray diagrams by drawing the path of the rays in the glass medium. Justify your answers.

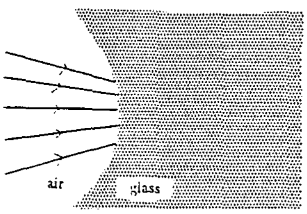
(a).



(b).



(c).

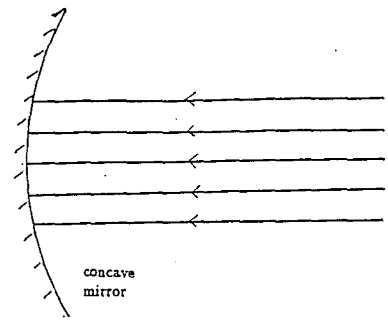


B.6 Reflection at curved surfaces

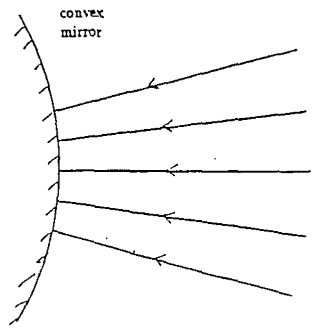
Answer ALL the questions, providing detailed explanations for each answer. If you feel a question is ambiguous, explore and provide answers for all the possibilities. The spaces provided are not indicative of the length of the answer.

1. Complete the path of the rays for the following. Provide an explanation for each answer.

(a).

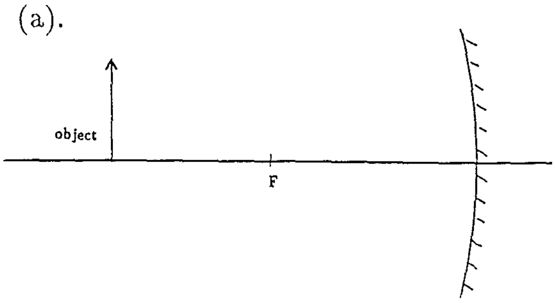


(b).

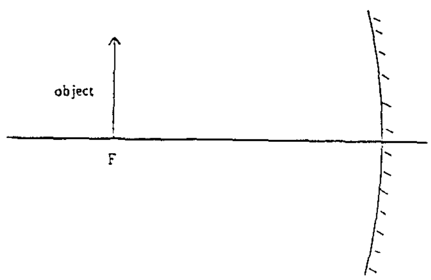


2. In each of the diagrams given below, the focal point of the mirror is indicated. Use rays to locate the image in each case. Describe the nature of the image formed.

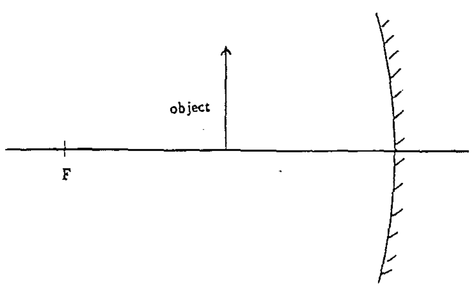
(a).



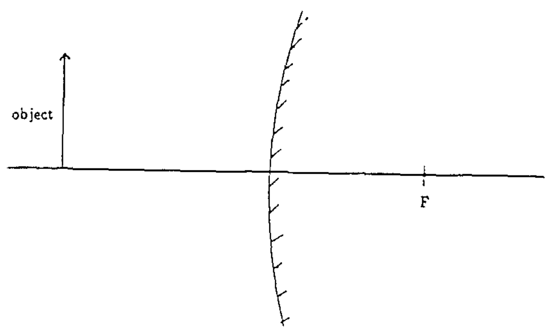
(b).



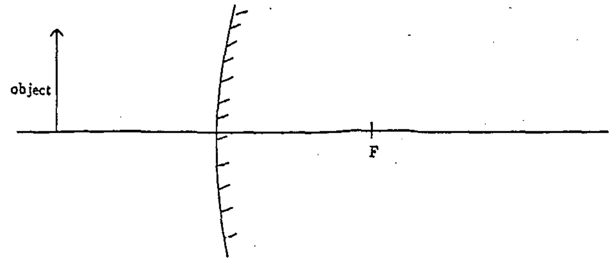
(c).



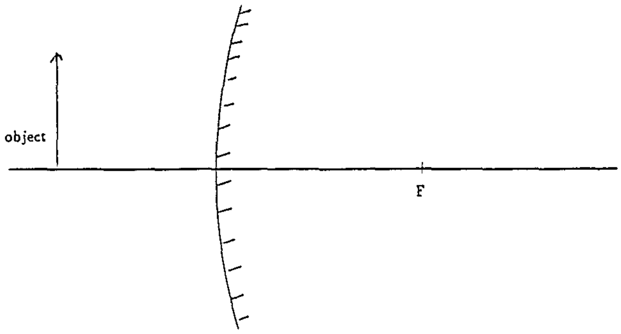
(d).



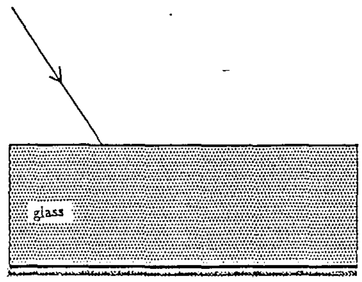
(e).



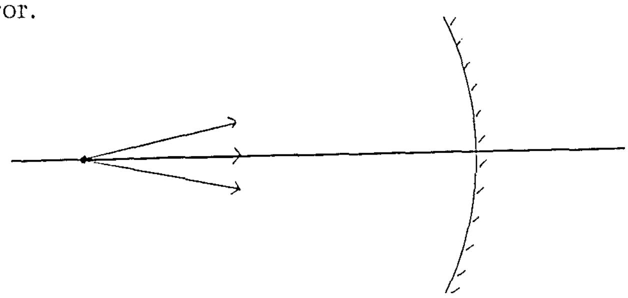
(f).



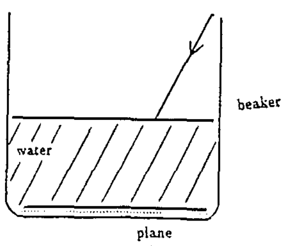
3. The diagram below shows a ray incident on a transparent glass block silvered at its base. Complete the path of the ray, taking all the possibilities into account.



4. The diagram below shows three rays being directed towards a concave mirror from its centre of curvature. Complete the paths of the rays showing their directions after reaching the mirror.



5. The diagram below shows a ray of light incident on the surface of water in a beaker. A plane mirror has been placed at the base of the beaker. Complete the path of the ray, taking all possibilities into account. Provide an explanation for your answer.

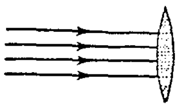


B.7 Refraction in lenses

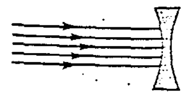
Answer all the questions, providing detailed explanations for each answer. If you feel a question is ambiguous, explore and provide answers for all the possibilities. The spaces provided for the answers are not indicative of the length of the answer.

1. Complete the path of the rays through the lenses. Provide an explanation for each answer.

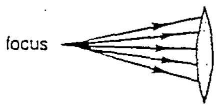
(a).



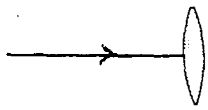
(b).



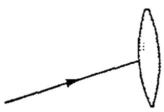
(c).



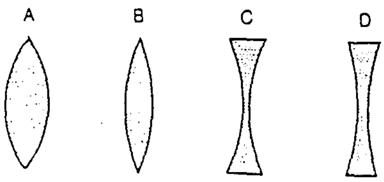
(d).



(e).



2.



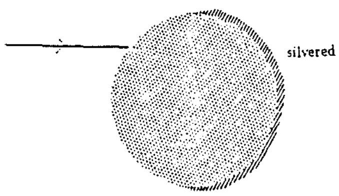
(a). Which lens has the longest focal length. Why ?

(b). Which lens has the shortest focal length. Why ?

(c). Which lens would you choose as a magnifying glass ? Justify your choice.

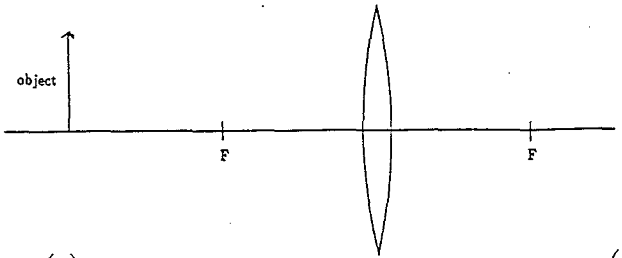
3. A photographer wishes to make an exact copy of a document. He has a copy camera with a focal length f. How far from the lens should he place the document and film ? Explain your answer.

4. The diagram below shows a glass sphere silvered on one half. A ray of light is shown incident on the sphere. Complete the path of the ray until it exits the sphere. Explain your answer.

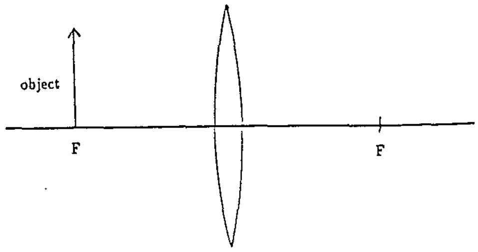


5. In each of the diagrams given below, use rays to accurately locate the image. Describe the nature of the image in each case.

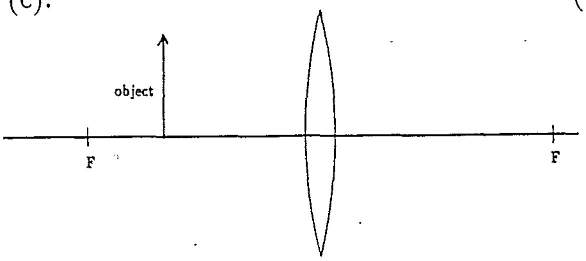
(a).



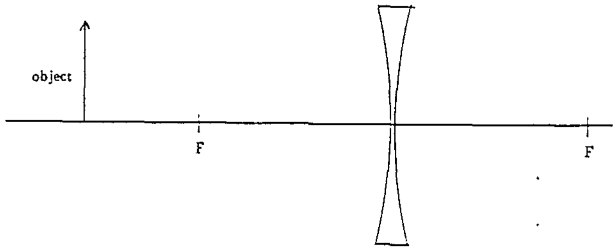
(b).



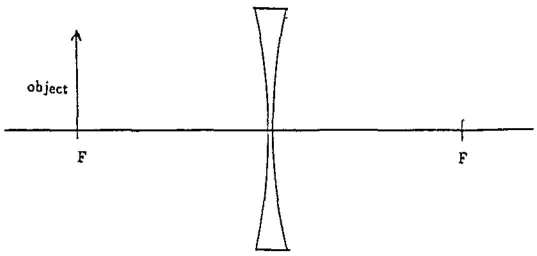
(c).



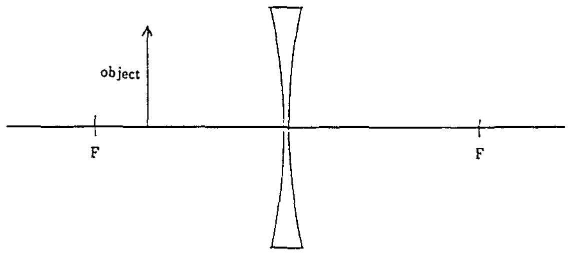
(d).



(e).



(f).

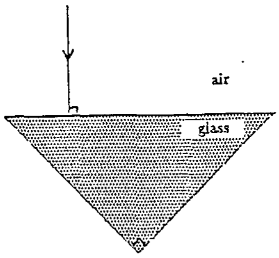


B.8 Refraction with prisms

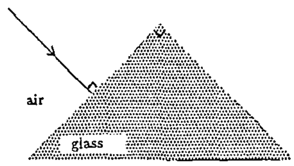
Answer all the questions, providing detailed explanations for each answer. If you feel a question is ambiguous, explore and provide answers for all the possibilities. The spaces provided for the answers are not indicative of the length of the answer.

1. Complete the path of the rays through the prisms and provide an explanation for each answer.

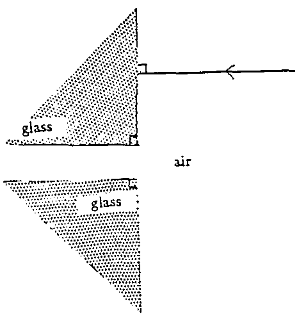
(a).



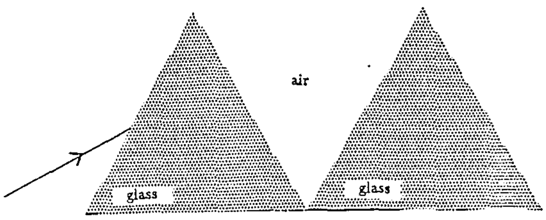
(b).



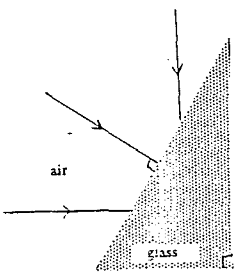
(c).



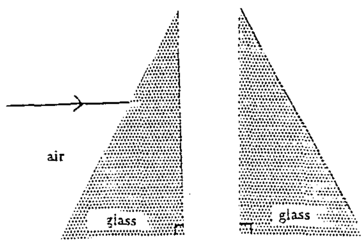
(d).



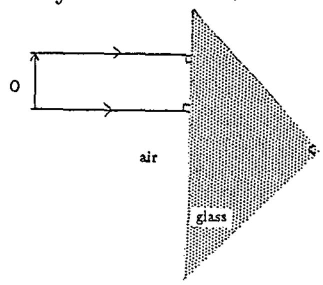
(e).



(f).

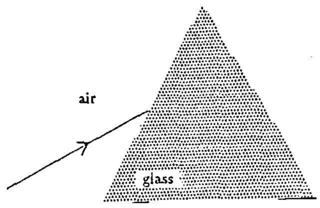


2. Two rays from an object O are incident on the face of a prism as shown in the diagram below. Complete the path of the rays through the prism and describe the nature of the image that may be observed.

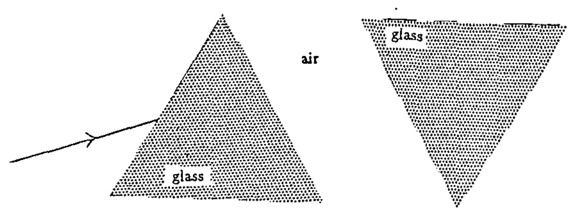


3. The diagrams below show a ray of sunlight incident on the face of a prism. The prisms are identical. Complete the path of the ray through the prisms providing an explanation in each case.

(a).



(b).



Appendix C

Questionnnaires on Mechanics

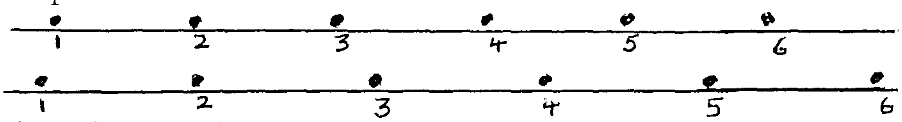
The optics questions used for data collection are included in this section. Beneath each question spaces were provided for the answers. The questionnaire titles were not included in the actual questionnaires.

C.1 Linear motion

Answer **ALL** the questions, providing explicit explanations answer. Most of the questions are open ended. If you feel a question is ambiguous, explore and provide answers for all the possibilities. You may put forth more than one explanatory answer to each question. The spaces provided for the answers are not indicative of the length of the answer.

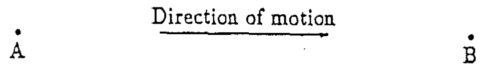
IGNORE AIR RESISTANCE FOR ALL QUESTIONS

1. The positions occupied by two balls moving on separate tracks at times 1, 2, 3, 4, ...6, are indicated in the figure below. The two balls A and B are moving at constant speeds.



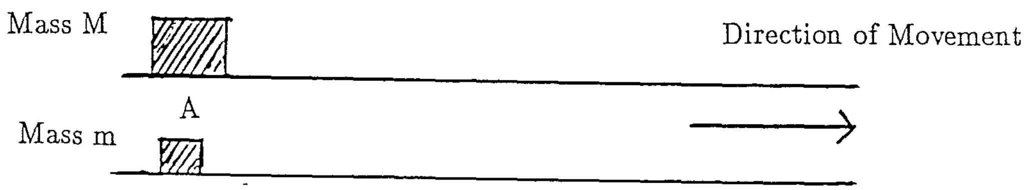
Are the speeds of the two balls ever equal?

Questions 2 and 3



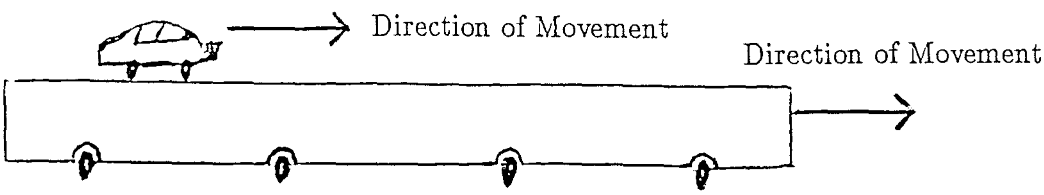
Car X starts from rest at point B and uniformly accelerates. At the same instant car Y is at point A and moving with uniform speed.

2. Will car Y be able to overtake car X?
3. Is there a time when X and Y have the same speeds?
4.



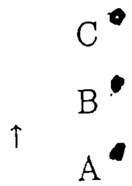
Two objects of different masses M and m ($M\ m$) are given a similar push at point A and are simultaneously set into motion. They travel in parallel paths along two horizontal, frictionless tracks. Describe and compare the motion of the two masses.

5.



The diagram shows a long railway wagon carrying a car which is moving with a uniform velocity. The railway wagon is also moving with a uniform velocity. Will the car reach the front end of the wagon?

For questions 6 to 9



The figure shows a ball thrown vertically upwards from point A on a high building. The ball reaches a point higher than C. B is a point halfway beetween A and C. Upon reaching its highest point above C the ball reverses direction to fall straight down.

6. Draw and label the force(s) acting on the ball on its way
(a) up (b) down

7. How do the speeds of B and C compare?

8. On its way down, how does the speed of the ball as it passes B compare to its speed as it passed B on its way up?

9. On its downward path, will the ball ever reach a maximum speed?

10. A person drops simultaneously two unequal masses M and m ($M\ m$) from the top of a tall building. The masses drop vertically. Compare the motions of the masses until they hit the ground.

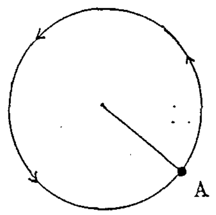
11. In question 10, if the masses are simultaneously thrown vertically down with the same strength, how would their motions then compare?

C.2 Circular motion

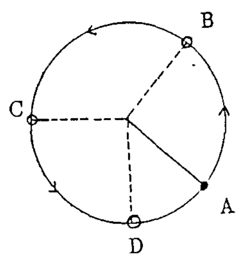
Answer **ALL** the questions, providing explicit explanations answer. Most of the questions are open ended. If you feel a question is ambiguous, explore and provide answers for all the possibilities. You may put forth more than one explanatory answer to each question. The spaces provided for the answers are not indicative of the length of the answer.

IGNORE AIR RESISTANCE FOR ALL QUESTIONS

1. The figure below shows an object attached to one end of a string and rotating on a horizontal, frictionless surface. The other end of the string is fixed at O. The string breaks when the object is in position A. Draw the path taken by the object.

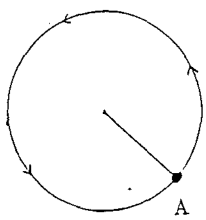


For Questions 2 and 3



The figure shows an object rotating in a vertical circle, at the end of a string. The other end of the string is fixed at O.

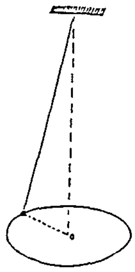
2. Draw and label the forces acting on the ball when rotating in position A. Use the diagram given below.



3. Draw the path taken by the object if the string breaks when the object is in position

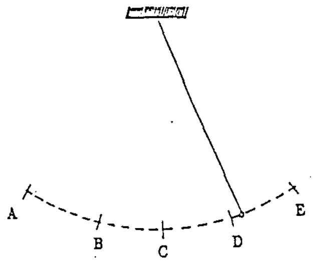
(a) A (b) B (c) C (d) D

4.



The diagram above represents a small body revolving in a horizontal circle, at the end of a string. The body swings around its path at a constant speed. Draw and label the force(s) acting on the body.

Questions 5 and 6



The diagram shows a small body oscillating to and fro in a vertical plane between points A and E. Draw and label the forces acting on the body when it is in position:

5. (i) B, on it way to C. (ii) C, on its way to D. (iii) D, on its way to E. (iv) When it arrives at E.

6. While the body is oscillating the string is cut. Draw the path that the body will take if the string is cut

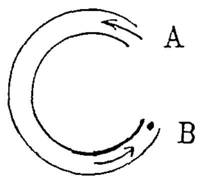
(i) in position B while the body is on it way to C. (ii) in position C while the body is on its way to D. (iii) in position D while the body is on its way to E. (iv) when it arrives at E.

C.3 Curved motion

Answer **ALL** the questions, providing explicit explanations for each answer. Most of the questions are open ended. If you feel a question is ambiguous, explore and provide answers for all the possibilities. You may put forth more than one explanatory answer to each question. The spaces provided for the answers are not indicative of the length of the answer.

IGNORE AIR RESISTANCE FOR ALL QUESTIONS

For questions 1 and 2



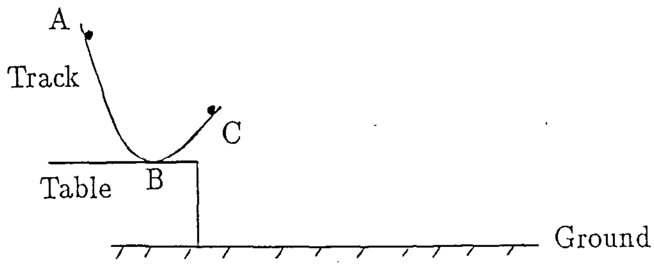
The accompanying figure shows a hollow, circular tube fixed to a frictionless, horizontal table. You are looking down at the table. A ball is shot into the end A of the tube to leave the other end B at high speed.

1. Draw the path of the ball after it leaves the tube at B.

2. Compare the velocity of the ball along the path that you have drawn with the ball's velocity at B.

For questions 3 and 4

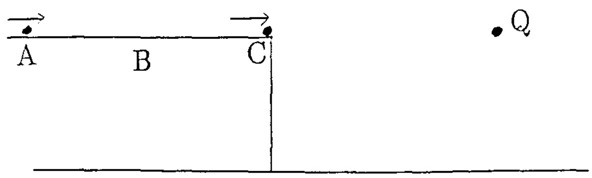
The figure below shows an object in motion in a vertical plane along a frictionless track. The object starts at A, moves down to B, and moves up to C where it leaves the track.



3. Draw the path taken by the object as it leaves the track at C. Use the diagram above.

4. Draw and label the force(s) acting on the object at three points along the path you have drawn.

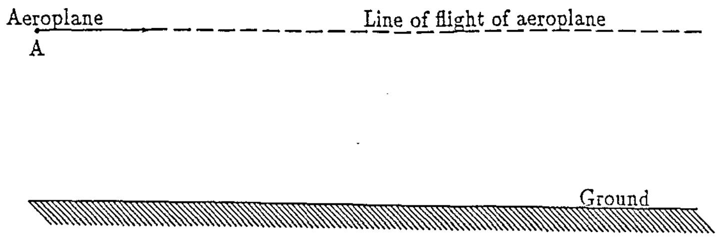
Questions 5 to 9:



The left side of the figure shows an object P set in motion on a horizontal, frictionless table ABC by being given a push at A. The object leaves the track at C.

5. How do the speeds of the object compare at A, B and C?

6. Draw the path taken by the object after it leaves the table at C. Use the diagram above.
7. What happens to the speed of the object along the path you have drawn?
8. Draw and label the force(s) acting on the object at B and two other points along the path you have drawn.
9. At the same time that the object P leaves C, an identical object Q is released from rest at the same height as shown in the diagram above. Which object reaches the ground first?
10.



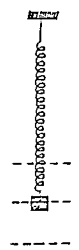
The figure above shows the horizontal direction in which an aeroplane is flying with constant speed. It releases a bomb at point A. Draw the path taken by the bomb in falling to the ground. Use the diagram above. Mark four positions of the bomb along the path that you have drawn. For each of these, indicate the corresponding position of the aeroplane.

C.4 Oscillatory motion

Answer ALL the questions, providing explicit explanations answer. Most of the questions are open ended. If you feel a question is ambiguous, explore and provide answers for all the possibilities. You may put forth more than one explanatory answer to each question. The spaces provided for the answers are not indicative of the length of the answer.

IGNORE AIR RESISTANCE FOR ALL QUESTIONS

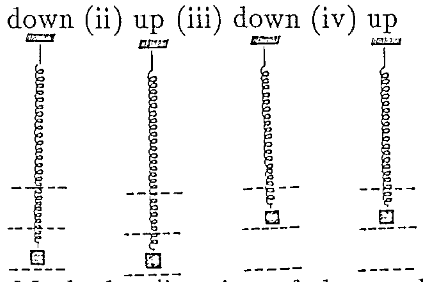
Questions 1 to 3



An object hanging from a spring is set into up and down motion between A and B. O is the centre of oscillation.

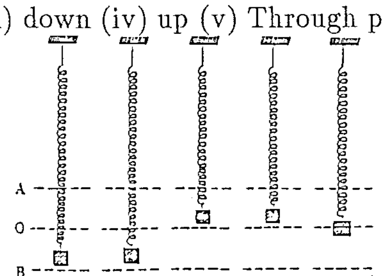
1. Draw and label the force(s) acting on the object when it is in the position shown and is moving

(i) down (ii) up (iii) down (iv) up



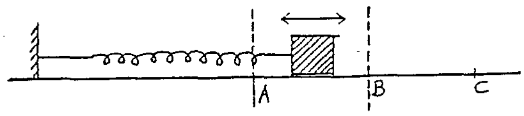
2. Mark the direction of the acceleration of the body when it is in the position shown and is moving

(i) down (ii) up (iii) down (iv) up (v) Through position O on its way up or down



3. While the object is moving up, the spring becomes detached from the object. Draw the subsequent path of the object and give a description of the motion.

Questions 4 to 7



An object connected to the end of a spring is oscillating to and fro between points A and B, on a horizontal, frictionless table. The other end of the spring is fixed to a support.

4. Draw and label the force(s) acting on the object.

5. While the object is on its way from A to B the spring breaks. Describe the subsequent motion of the object.

6. Draw and label the force(s) acting on the object after the spring breaks.

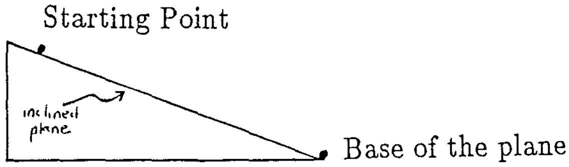
7. How does the velocity of the object compare in positions B and C?

C.5 Connected particles and motion along inclined planes

Answer **ALL** the questions, providing explicit explanations answer. Most of the questions are open ended. If you feel a question is ambiguous, explore and provide answers for all the possibilities. You may put forth more than one explanatory answer to each question. The spaces provided for the answers are not indicative of the length of the answer.

IGNORE AIR RESISTANCE FOR ALL QUESTIONS

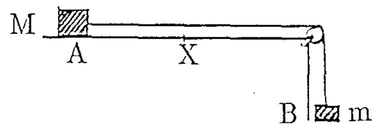
Questions 1 and 2



A disc and a cylinder of equal mass are timed in their motion down an inclined plane over the same distance. Which will reach the base of the plane in a shorter time if the plane is

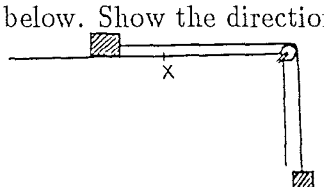
1. Frictionless, so neither object rolls.
2. Rough, so both the disc and the cylinder roll down the plane.

Questions 3 to 7



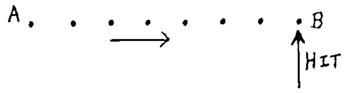
Blocks A and B are connected by a string that passes over a frictionless pulley. Block A is held stopping the blocks from moving. Block A lies on a horizontal, frictionless surface.

3. Explain the motion of the blocks when block A is released.
4. Draw and label all the forces acting on each of the blocks when in motion. Use the diagram below. Show the direction of motion of the blocks.



5. When block A reaches X, the string breaks. Describe the motion of the two blocks after the string breaks.
6. Draw and label the forces acting on each block after the string breaks.
7. If in Question 3 the block B is replaced by a block C of twice the mass, will the motion of block A be different?

Questions 8 and 9

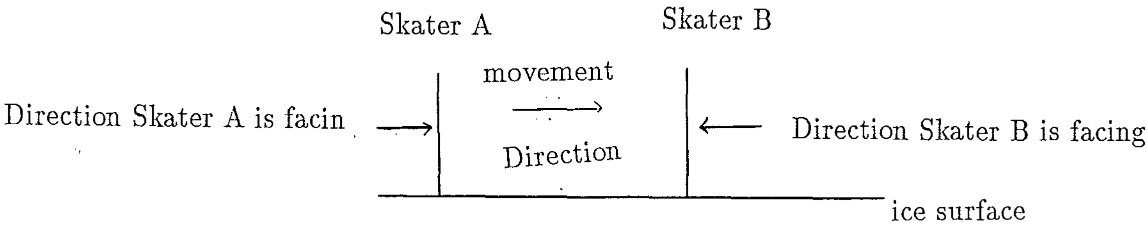


In the figure above you are looking down at a ice-hockey puck sliding at constant speed on a frictionless, horizontal surface. When the puck reaches point B, it receives a horizontal hit in the direction shown.

8. Draw the path that the puck will follow after it receives the hit.

9. What happens to the speed of the puck when it receives the hit?

Questions 10 and 11



Two skaters facing each other are moving with equal speeds as shown above (A is skating forward and B is skating backwards). While they are moving, A throws a ball to B who catches it.

10. Compare the motion of A before and after throwing the ball.

11. Compare the motion of B before and after catching the ball.

Appendix D

Card sets used for Free Sorting

D.1 Words Commonly Used in Physics

Acceleration	Action	Combustion
Conductivity	Critical	Density
Dimensions	Dispersion	Distance
Elasticity	Equilibrium	Equipotential
Force	Frequency	Fusion
Induction	Inertia	Intensity
Magnification	Oscillation	Parallel
Period	Phase	Polarization
Potential	Pressure	Reaction
Resistance	Resolution	Resonance
Resultant	Rotational	Scalar
Series	Speed	Time
Transverse	Units	Vapourization
Vector		

D.2 Mechanics Words

Acceleration	Action	Amplitude
Angular Momentum	Centre of Mass	Centripetal Acceleration
Cross Product	Damped	Density
Displacement	Dot Product	Driving Force
Elastic	Force	Forced
Free Fall	Frequency	Friction
Gravitational Force	Hooke's Law	Impulse
Inelastic	Kinetic Energy	Length
Mass	Modulus of Elasticity	Moment of Inertia
Momentum	Oscillations	Pendulum
Period	Phase	Potential Energy
Pressure	Projectile	Reaction
Resonance	Restoring Force	Rigid Body
Rotational Motion	Specific Gravity	Speed
Spring Constant	Strain	Stress
Superposition	Tension	Time
Time of Flight	Torque	Translational Motion
Upthrust	Vector	Velocity
Wave	Weight	Work

D.3 Physics Words

Aberration	Acceleration	Adiabatic
Beats	Blackbody	Calorimetry
Capacitor	Carnot Cycle	Conduction
Convection	Converging	Current
Diamagnetic	Dielectric	Diffraction
Displacement	Diverging	Ferromagnetic
Flux	Focus	Force
Friction	Gravity	Heat Capacity
Image	Impedance	Inductor
Interference	Isothermal	Lens
Longitudinal	Mass	Paramagnetic
Permittivity	Pitch	Polarization
Potential	Projectile	Radiation
Reactance	Real	Reflection
Refraction	Resistance	Resonance
Scattering	Solenoid	Sound
Temperature	Torque	Velocity
Virtual	Voltage	Wave
Wavelength	Weight	

D.4 Words with a meaning in physics and everyday life

Action	Charge	Combustion
Conduction	Conductor	Converging
Couple	Critical	Density
Dispersion	Diverging	Elastic
Energy	Equilibrium	Field
Gradient	Image	Insulator
Intensity	Magnitude	Medium
Normal	Oscillation	Pendulum
Phase	Pitch	Polarization
Power	Pressure	Primary
Radiate	Reaction	Real
Resistance	Resolving	Rigid
Secondary	Standing	State
Strain	Stresses	Tangential
Temperature	Tension	Tone
Wave	Work	

D.5 Principles and Laws of Physics

Ampere's Law
Archimedes' Principle
Biot - Savart Law
Boyle's Law
Carnot's Theorem
Charles' Law
Conservation of Angular Momentum
Conservation of Charge
Conservation of Energy
Conservation of Mass
Conservation of Mechanical Energy
Conservation of Momentum
Coulomb's Law of Force
Faraday's Law
Field Theory
First Law of Thermodynamics
Gauss' Law
Hooke's Law
Huygen's Principle
Ideal Gas Law
Inverse Square Law
Kepler's Laws
Kinetic Theory
Kirchhoff's Rule
Law of Reflection
Law of Refraction
Lenz's Law
Mass - Energy Theorem
Momentum - Impulse Principle
Newton's First Law
Newton's Law of Universal Gravitation
Newton's Second Law
Newton's Third Law
Ohm's Law
Pauli's Exclusion Principle
Planck's Radiation Law
Principle of Equipartition of Energy
Principle of Superposition
Quantization of Angular Momentum
Quantization of Charge
Resonance Effect

Snell's Law
Stefan - Boltzmann Law
Uncertainty Principle
Wien's Displacement Law
Work - Energy Principle

D.6 Equations in Physics

$\chi_c = \frac{1}{\omega C}$	$J = \frac{I}{A}$	$n_1 \sin\theta_1 = n_2 \sin\theta_2$
$\varepsilon = -L\frac{dI}{dt}$	$E_p = -G\frac{mM}{r}$	$\tau = I\alpha$
$F\Delta t = m\Delta v$	$V = IR$	$(n - \frac{1}{2})\lambda = d\mathrm{sin}\theta$
$J = nev$	$F = Eq$	$y = A\mathrm{sin}\omega t$
$L = I\omega$	$F = ma$	$W = Eqd$
$W = \frac{1}{2}QV$	$E = \frac{1}{2}m\omega^2A^2$	$\lambda = \frac{xd}{L}$
$PV = nRT$	$\tau = Fr$	$d = v_it + \frac{1}{2}at^2$
$\chi_L = \omega L$	$E_p = mgh$	$Q = It$
$F = BIl$	$E_p = \frac{1}{2}kx^2$	$n = \frac{\lambda_{air}}{\lambda_{medium}}$
$PV = NkT$	$E_{kr} = \frac{1}{2}I\omega^2$	$a = r\alpha$
$F = \frac{kI_1I_2l}{d}$	$p = mv$	$v_f{}^2 = v_i{}^2 + 2ad$
$W = \frac{1}{2}LI^2$	$R = \rho\frac{l}{A}$	$Q = mc\Delta T$
$f = \frac{1}{2}R$	$E = -\frac{\Delta V}{\Delta r}$	$T = 2\pi\sqrt{\frac{m}{k}}$
$k = \frac{2\pi}{\lambda}$	$E_k = \frac{1}{2}mv^2$	$v = \frac{2\pi R}{T}$
$I = nevA$	$V = Bvl$	$f = \frac{1}{2\pi\sqrt{LC}}$
$E = \rho J$	$v = \frac{c}{n}$	$v = f\lambda$
$T = 2\pi\sqrt{\frac{l}{g}}$	$I = \Sigma m_ir_i{}^2$	$v\prime = \frac{v}{1 \pm \frac{v_E}{v}}$
$\frac{\Delta Q}{\Delta t} = -kA\frac{dT}{dx}$	$V = \frac{W}{q}$	$F = Bev$
$P = \frac{W}{t}$	$a = \frac{4\pi^2R}{T^2}$	$Q = CV$
$S_iS_o = f^2$	$T = \frac{1}{f}$	$Q = mL$
$F = \frac{kq_1q_2}{r^2}$	$B = \frac{kI}{d}$	$v = r\omega$
$W = Fd$	$C = \epsilon_o\frac{A}{d}$	$a = \frac{v^2}{R}$
$P = VI$	$F = \frac{Gm_1m_2}{r^2}$	$y = A\mathrm{sin}(kx + \omega t)$
$P = \rho gz$	$f_b = f_1 - f_2$	

D.7 Mechanics Equations

$$I\frac{d^2\theta}{dt^2} = \tau$$
$$\vec{F} = \frac{dp}{dt}$$
$$\int \vec{F}dt = \int d\vec{p}$$
$$P = \frac{\Delta F}{\Delta A}$$
$$\vec{p} = m\vec{v}$$
$$\alpha = \frac{d\omega}{dt}$$
$$\omega = \frac{d\phi}{dt}$$
$$I = \Sigma m_i {R_i}^2$$
$$\omega = \omega_o + \alpha t$$
$$F = \frac{mv^2}{r}$$
$$P = \tau\omega$$
$$v = R\omega$$
$$t_{flight} = \frac{2v_o \sin\theta}{g}$$
$$F = -kx$$
$$\omega = \sqrt{\frac{\kappa}{I}}$$
$$\omega = \sqrt{\frac{Mgl}{I}}$$
$$U = \frac{1}{2}kx^2$$
$$E = \frac{1}{2}kA^2$$
$$x - x_o = v_o t + \frac{1}{2}at^2$$
$$a(x - x_o) = \frac{1}{2}(v^2 - {v_o}^2)$$

$$P = \frac{dW}{dt}$$
$$\nu = \frac{1}{T}$$
$$\tau = -\kappa\theta$$
$$E = mc^2$$
$$\frac{d\vec{L}}{dt} = \vec{r} \times \vec{F}$$
$$L = rp = mvr$$
$$T = \frac{2\pi}{\omega}$$
$$W = \int \tau d\phi$$
$$U = mgh$$
$$a = \omega^2 R$$
$$\frac{d\vec{L}}{dt} = \vec{\tau}$$
$$\tau = I\alpha$$
$$x_{max} = \frac{{v_o}^2 \sin 2\theta}{g}$$
$$\frac{d^2x}{dt^2} = -\omega^2 x$$
$$\omega = \sqrt{\frac{\kappa}{m}}$$
$$m\frac{d^2x}{dt^2} = -kx$$
$$v = \frac{dx}{dt}$$
$$E = -\frac{GM_e m}{2r}$$
$$F = \frac{GMm}{r^2}$$
$$P_{atm} = \rho g h$$

$$F = -\frac{dU}{dx}$$
$$W = \int F dx$$
$$P = \vec{F}.\vec{v}$$
$$\vec{F} = m\vec{a}$$
$$\nu = \frac{\omega}{2\pi}$$
$$I_z = I_x + I_y$$
$$I = I_{cm} + Md^2$$
$$L = I\omega$$
$$a = \frac{v^2}{r}$$
$$\vec{L} = \vec{r} \times \vec{p}$$
$$K = \frac{1}{2}I\omega^2$$
$$a = \frac{dv}{dt}$$
$$w = mg$$
$$x = A\cos(\omega t + \delta)$$
$$T = 2\pi\sqrt{\frac{l}{g}}$$
$$I\frac{d^2\theta}{dt^2} = -\kappa\theta$$
$$K = \frac{p^2}{2m}$$
$$U = -\frac{GMm}{r}$$
$$f_k = \mu_k N$$

Bibliography

[1] Bowden J W, Stonehouse H G and Vincent B A 1972 Readings in fifth form Science: Physics Reed Education.

[2] Bruner J, Goodnow J J and Austin G A 1980 Concept Attainment: The Basics of Thinking In B Joyce and M Weil (ed.) Models of Teaching, second edition, Prentice-Hall, New Jersey.

[3] Cambridge Examination Syndicate Syllabus guide for A-level Physics, Cambridge, U.K.

[4] Castle T 1986 A Physics Guidebook for Form Six Heinemann Guidebook Series, Hong Kong.

[5] Champagne A B, Klopfer L E, Desena A T and Squires D A 1981 Journal of Research in Science Teaching Structural representations of students' knowledge before and after science instruction 18(2), 97-111.

[6] Chase N and Simon H A 1973a The minds eye in chess In W G Chase (ed.) Visual information processing Academic Press, N. Y.

[7] Chase N and Simon H A 1973b Cognitive Psychology Perception in chess 4, 55-91.

[8] Chi M T H, Feltovich P J and Glaser R 1981 Cognitive Science Categorization and representation of physics problems by experts and novices 5, 121-152.

[9] Clement J 1982 American Journal of Physics Students' preconceptions in introductory mechanics 50(1), 66-71.

[10] DeCourcy J and Epp D 1982 Physics Heinemann New Science Series.

[11] Dept of Educ 1978 Science: Forms one to four Syllabus Guide Wellington, New Zealand.

[12] Driver R and Erickson G 1983 Studies in Science Education Theories-in-Action: Some Theoretical and Empirical Issues in the Study of Students' Conceptual Frameworks in Science 10, 37-60.

[13] Erickson G and Hobbs E 1978 A development study of students beliefs about force concepts A paper presented at the 1978 Annual Convention of the Canadian Society for the Study of Education, June.

[14] Gilbert J K and Watts D M 1983 Studies in Science Education Concepts, Misconceptions and Alternative Conceptions: Changing Perspectives in Science Education 10, 61-98.

[15] Gilbert J, Watts D M and Osborne R 1982 Physics Education Student conceptions of ideas in mechanics 17, 62-66.

[16] Greeno J G 1978 Natures of problem solving abilities In W K Estes (Ed.) Handbook of learning and cognitive processes. Vol 5, Hillsdale, N J, Lawrence Erlbaum Associates.

[17] Guesne E 1981 Workshop presented at the International Conference of Physics Teaching Children's conceptions of light. Sept, Trieste, Italy.

[18] Halhoun I A and Hestenes D 1985 American Journal of Physics Common sense concepts about motion 53, 1056-1065.

[19] Halliday D and Resnick R 1988 Fundamentals of Physics Third Edition, John Wiley & Sons, N. Y.

[20] Hewson P W 1981 The Australian Science Teachers' Journal Aristotle: Alive and well in the classroom? 27(3), 9-13.

[21] Jira D, McCloskey M and Green B 1981 Problem Solving Students misconceptions about motion 2(3).

[22] Johnson P E 1964 Journal of Educational Psychology Associative Meaning of Concepts in Physics 4(2), 84-88.

[23] Jung W 1981 Paper presented at the International Workshop on the problems concerning students' representation of physics and chemistry knowledge Conceptual frameworks in elementary optics Sept, Ludwigsburg.

[24] Linn M C 1986 Science In Cognition and Instruction (Ed.) R F Dillon and R J Steinberg Academic Press Inc., Harcourt Brace Jovanovich, Florida, USA.

[25] McCloskey M, Caramazza A and Green B 1980 Science Curvilinear motion in the absence of external forces: Naive beliefs about the motion of objects 210, 1139- 1141.

[26] McCloskey M 1983 Scientific American Intuitive Physics 248(4).

[27] McDermott L C 1987 Paper presented at the regional Physics Education symposium on school-University Interface and ASPEN General Conference Bridging the gap in Physics between school and university. Oct, K L, Malaysia

[28] Min of Educ, 1960-1990 Syllabus for Science Singapore.

[29] Munroe R 1989 NZ Science Teacher The Misrepresentation of Science: A Teacher's Dilemma (The Roger Osborne Memorial Address) 59, 8-16.

[30] Ohanian H C 1985 Physics W W Norton & Co., N Y

[31] Osborne R and Freyberg P 1985 Learning in Science: The implications of children's science Heinemann, Auckland, NZ.

[32] Osborne R and Stead B 1980 Australian Science Teachers' Journal Exploring science students' concepts of light 26(3), 84-90.

[33] Sears F W, Zemansky M W and Young H D 1987 University Physics Addison- Wesley, Reading, Massachusetts.

[34] diSessa A 1982 Cognitive Science Unlearning Aristotelian physics: a study of knowledge based learning 6(37).

[35] Shavelson R J 1973a Journal of Research in Science Teaching Learning from Physics between context structure and cognitive structure in physics instruction 63, 225- 234.

[36] Shavelson R J 1973b Journal of Educational Psychology Some aspects of the correspondence between context structure and cognitive structure in physics instruction 63, 225-234.

[37] Shavelson R J 1974 Journal of Research in Science Teaching Methods for examining representations of subject matter structure in a students memory 11(3), 231-249.

[38] Singh A and Butler P H 1989a Proceedings of the ASPEN conference and workshop on the Teaching of Optics Geometrical Optics: Knowledge of Students Sept, Melbourne, Australia.

[39] Singh A and Butler P H 1989b Preprint University of Canterbury Reflection of Light: Conceptions, Structure and Approach Christchurch, N Z.

[40] Singh A and Butler P H 1989c Preprint University of Canterbury Refraction: Conceptions and Knowlege Structure Christchurch. N Z.

[41] Singh A and Butler P H 1989d Preprint University of Canterbury Effect of Knowledge Base on Conceptions in Mechanics Christchurch, N Z.

[42] Stonehouse H G 1980 Thinking about Science: Radiant Energy Longmans.

[43] University Entrance Board 1989 University of Canterbury Handbook University Entrance and Bursary Prescription Christchurch, N. Z.

[44] Viennot L 1979 European Journal of Science Education Spontaneous learning in elementary dynamics 1(2), 205-221.

[45] Watts D M and Zylbersztajn A 1981 Physics Education A survey of some children's ideas about force 15, 360-365.